UNIVERSITÉ DE MONTRÉAL

THERMAL BEHAVIOR OF DRY-TYPE TRANSFORMER

DA WEI ZHU
DÉPARTEMENT DE GÉNIE ÉLECTRIQUE
ÉCOLE POLYTECHNIQUE DE MONTRÉAL

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Ce mémoire intitulé:

THERMAL BEHAVIOR OF DRY-TYPE TRANSFORMER

Présenté par: DA WEI ZHU

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M. SIROIS Frédéric, Ph.D., président

M. OLIVIER Guy, Ph.D. membre et directeur de recherche

M. ARFA Khaled, Ph.D., membre

To My Parents

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RÉSUMÉ

L'augmentation de la température est l'un des paramètres influençant le plus la durée de vie des transformateurs ; cet échauffement peut même causer de sérieux dommages aux transformateurs. L'estimation de la température est alors importante pour les ingénieurs et les constructeurs. De plus, il n'est pas évident de connecter le transformateur à la pleine charge en usine. Bien que ceci simulerait plus directement le transformateur dans les conditions d'opérations, la puissance entrante du test se dissiperait dans la charge. Comme l'augmentation de la température dans un transformateur dépend de beaucoup de paramètres, l'estimation de cette augmentation est toujours une procédure compliquée.

Dans ce projet, nous allons nous intéresser expérimentalement au comportement thermique de deux transformateurs de 30 kVA de distribution de type à sec, et effectuer une comparaison approfondie entre la méthode des pertes à excitation séparée et à courant nominal et la méthode en opposition sur deux transformateurs pour déterminer leur comportement thermique et valider les équations trouvées dans la norme IEEE C57.12.91 - 2001.

Ce projet comprend également :

- La mise en service d'un banc de test comprenant l'alimentation et les appareils de mesures.
- La mesure des pertes dans le noyau et dans les enroulements pour les tests en circuit ouvert, en court-circuit et en charge pour deux transformateurs de 30kVA.
- Le calcul et l'analyse de l'augmentation de température pour deux transformateurs réels.

ABSTRACT

Temperature rise is one of the most critical factors that affect the reliability of transformer. Excessive rise can easily lead to serious damages to the transformers. Therefore, temperature estimation plays an important role in engineering for commercial companies. Moreover, it is also not practical to connect the transformer for loading with full rated capacity at the end of the assembly process. Although this would directly simulate the transformer operating condition, the total input power will be dissipated in the load.

In fact, the transformer temperature rise depends on several factors which make temperature estimation complicated and a sophisticated procedure. In this project, based on extensive experimental measurements on two 30 kVA dry-type transformers, we compare the separate excitation loss and rated current method and the loading back method in order to determine their thermal behavior and validate equations found in standard IEEE C57.12.91 - 2001.

This project includes:

- Commissioning of the test bench including the power supply and the measurement apparatus.
- Core losses and winding losses measurements in open circuit, short circuit and loading back test of two 30kVA dry type transformer.
- Calculation and analysis of the temperature rise of two real transformers.

CONDENSÉ EN FRANÇAIS

Dans ce mémoire, fondées sur des mesures expérimentales sur deux transformateurs de type sec de 30 kVA, nous avons comparé la méthode des pertes par excitation séparée et à courant nominal avec la méthode en opposition, afin de déterminer leur comportement thermique et de valider les équations trouvée dans C57.12.91 norme IEEE -2001.

0.1 OBJECTIF DE RECHERCHE

Lorsqu'ils sont en fonctionnement, les transformateurs réels produisent des pertes thermiques provenant de la perte de puissance dans le noyau et dans les enroulements. Si la température de chaque partie du transformateur (noyau et enroulements) dépasse la température maximale acceptable, une dégradation rapide ou même une panne catastrophique de l'isolant pourrait se produire.

L'élévation de température dans un transformateur dépend de plusieurs facteurs comme la température ambiante, le courant de charge et les types de noyau. Compte tenu de tous ces paramètres, l'estimation de l'élévation de température est toujours une procédure compliquée. En outre, il est aussi peu pratique de connecter le transformateur à une charge de capacité nominale à la fin du processus d'assemblage. Bien que cela simule directement les conditions de fonctionnement du transformateur, la puissance totale devrait se dissiper dans la charge.

Selon les normes ANSI et IEEE, plusieurs méthodes pour déterminer l'élévation de la température lors de test en charge peuvent être utilisées pour différents types de transformateurs à sec. Dans ce projet, la méthode des pertes par excitation séparée et à courant nominal et la méthode en opposition (aussi appelée méthode dos à dos) sera utilisée pour étudier l'élévation de température moyenne des enroulements.

0,3 L'AUGMENTATION DE TEMPERATURE MOYENNE ENROULEMENT

Selon la norme IEEE C57.12.91-2001, la hausse moyenne de température peut être déterminée par mesure de la résistance à froid et de la résistance à chaud. La résistance à froid est mesurée à température ambiante et la résistance à chaud sera déterminée après l'essai d'échauffement. Les équations ci-dessous sont utilisées pour déterminer la température moyenne d'enroulement T.

$$T = \frac{R}{R_0} \times (T_k + T_o) - T_k$$

ou

$$T = \frac{(R - R_0)}{R_0} \times (T_k - T_0) + T_0$$

L'échauffement moyen de l'enroulement est donné par la formule :

$$T_r = T - T_a$$

où :

T : température ($^\circ C$) correspondante à la résistance à chaud R,

T_o : température ($^\circ C$) correspondante à la résistance à froid R_o

T_r : élévation de température moyenne ($^\circ C$) de l'enroulement,

T_a : température ambiante à la fin d'essai ($^\circ C$) correspondant à la résistance à chaud R,

R_o : la résistance à froid déterminée selon les normes, ohms,

R : la résistance à chaud déterminée selon les règles de la norme, ohms,

T_k : 234.5 $^\circ C$ pour le cuivre,

T_k : 225 $^\circ C$ pour l'aluminium.

D'après l'équation ci-dessus, la résistance à froid (T0), la résistance à chaud (T) et la température ambiante sont des facteurs déterminants dans le calcul de l'augmentation de la température.

La température ambiante réelle est normalement déterminée à partir de thermomètres judicieusement situés dans la zone d'essai. En outre, selon la norme IEEE C57.12.91-2001 [1], il est conseillé que la température ambiante ne devrait pas être inférieure à 10 ° C ou supérieure à 40 °

0,3 MESURE DE LA RESISTANCE D'ENROULEMENT

La mesure de la résistance des enroulements doit être étudiés en deux parties: la mesure de la résistance à froid et la mesure de la résistance à chaud, qui vont permettre de déterminer la température de l'enroulement. La mesure de la résistance doit être faite sur toutes les prises nominales de chaque phase des enroulements primaires et secondaires.

Mesure de la résistance à froid

Normalement, les mesures de résistance à froid sont prises sur toutes les phases des enroulements primaires et secondaires avant de charger le transformateur pour l'essai d'échauffement. S'il y a différence entre les valeurs de résistance à froid, le transformateur doit être refroidi à la température ambiante après l'essai en charge, pour effectuer la mesure de résistance à froid.

Avant de mesurer la résistance à froid, il faut déterminer la température des enroulements aussi précisément que possible. La température des enroulements doit être enregistrée comme la lecture moyenne des trois thermocouples insérés entre les bobines. Les thermocouples doivent être en contact réel avec la surface des enroulements. Il ne faut pas supposer que la température ambiante est la même que la température des enroulements.

Dans notre cas, le micro-ohmmètre Multi-Amp 830280 est utilisé pour mesurer les résistances à froid des deux transformateurs.

Mesure de la résistance des enroulements à chaud

La résistance à chaud est mesurée lorsque la température de l'enroulement du transformateur est stabilisée en essai en court-circuit et en essai dos à dos, c'est-à-dire "la variation de la température de l'enroulement ne doit pas être plus de 2 °C pendant une période de 3 heures consécutive» [1]. Les lectures sont faites sur tous les enroulements de chaque phase et une courbe de refroidissement est tracée pour chaque enroulement de chaque phase. La première mesure sur chaque phase doit être prise aussi rapidement que possible après l'instant d'arrêt de l'alimentation électrique.

Mais il y a toujours un délai entre l'arrêt de l'alimentation et la première valeur de résistance mesurée. Dans notre laboratoire, un circuit a été fabriqué pour faciliter les connexions des sources de courant continu aux enroulements primaire et secondaire et au système d'acquisition de données. L'appareil de mesure a permis de mesurer simultanément la résistance de chaque bobinage. Un système d'enregistrement automatique des données permet d'effectuer une mesure de la résistance de chaque enroulement toutes les 10 secondes. Pour effectuer avec précision la mesure de la résistance juste après l'arrêt de l'alimentation, la courbe de refroidissement de la résistance sera extrapolée à l'instant d'arrêt de l'alimentation en utilisant le critère approprié pour calculer la résistance à chaud.

0,4 PERTES DANS LE NOYAU

Tant que le transformateur est connecté à une source alternative, il y aura un courant qui circule dans ses enroulements. Le courant circulant dans un enroulement est une conséquence directe des flux existants dans le noyau ferromagnétique, qui se divise en deux composantes: le courant de magnétisation I_{φ} et le courant de pertes fer I_{fe}. Les pertes de puissance dans le noyau affectent de manière notable la durée de vie des transformateurs. Les pertes d'excitation comprennent deux éléments principaux:

- les pertes par hystérésis, qui sont causées par l'inversement cyclique des flux dans le circuit magnétique.
- les pertes par courants de Foucault, qui sont causées par des courants de Foucault circulant au sein de l'acier induits par la circulation du flux magnétique perpendiculairement à la largeur du noyau.

La somme du courant de magnétisation et du courant de pertes dans le noyau est appelé le courant d'excitation. Il peut être exprimé comme suit:

$$I_{ex} = I_{\varphi} + I_{fe}$$

La résistance et la réactance du noyau peuvent être calculées comme suit:

Monophasé

$$\begin{cases} \cos\theta = \dfrac{P_{fe}}{E_{ex} I_{ex}} \approx \dfrac{P_{oc}}{E_{oc} I_{oc}} \\ R_{fe} = \dfrac{P_{fe}}{I_{fe}^{2}} = \dfrac{E_{oc}}{I_{oc} \times \cos\theta} \\ X_{\phi} = \dfrac{E_{oc}}{I_{oc} \times \sin\theta} \end{cases}$$

Triphasé

$$\begin{cases} \cos\theta = \dfrac{P_{fe}}{E_{ex} I_{ex}} \approx \dfrac{P_{oc}}{3 \times E_{oc} I_{oc}} \\ R_{fe} = \dfrac{P_{fe}}{I_{fe}^{2}} = \dfrac{E_{oc}}{3 \times I_{oc} \times \cos\theta} \\ X_{\phi} = \dfrac{E_{oc}}{3 \times I_{oc} \times \sin\theta} \end{cases}$$

où:

E_{oc}: tension en circuit ouvert (V)
I_{oc}: courant en circuit ouvert (A)
P_{oc}: pertes de puissance réelle (W)
P_{fe}: pertes fer dans le noyau (W)
R_{fe} and X_{φ} : la résistance et la réactance du noyau

Pour déterminer les pertes fer, l'essai en circuit ouvert est utilisé. Normalement, le test en circuit ouvert est de 24 heures à tension et fréquence nominales, afin de laisser la température du noyau se stabiliser. De plus, l'élévation de température due aux pertes d'excitation est déterminée en mesurant la résistance des enroulements à la fin de l'essai en circuit ouvert.

0.5 PERTES DANS LES ENROULEMENTS

Les pertes en charge dissipées par un transformateur dépendent de la charge connectée à l'enroulement secondaire. Les pertes en charge sont généralement obtenues à partir de l'essai en court-circuit en appliquant un courant de charge bien définie à la fréquence nominale sur un enroulement alors qu'un second enroulement est court-circuité. Dans ce cas, l'impédance de magnétisation est supposée être plus grande que la résistance secondaire et l'impédance de fuite et est négligeable.

Les pertes en charge du transformateur comprennent deux parties principales:

a) Les pertes produites par I^2R dues au courant de charge circulant dans l'impédance des enroulements;

b) Les pertes vagabondes dans certaines parties métalliques du transformateur dues aux courants de Foucault induits par le champ de fuite.

Mais pour la puissance nominale de petits transformateurs à sec, les pertes vagabondes sont généralement très petites, de 1% à 2% des pertes en charge. L'impédance équivalente peut être déterminée comme suit:

<u>**Monophasé**</u>	et	<u>**Triphasé**</u>
$Z_{eq} = \frac{E_{sc}}{I_{sc}}$		$Z_{eq} = \frac{E_{sc}}{\sqrt{3} \times I_{sc}}$
$R_{eq} = \frac{P_{sc}}{I_{sc}^2}$		$R_{eq} = \frac{P_{sc}}{3 \times I_{sc}^2}$
$X_{eq} = \sqrt{Z_{eq}^2 - R_{eq}^2}$		$X_{eq} = \sqrt{Z_{eq}^2 - R_{eq}^2}$

0,6 METHODOLOGIE

Dans ce projet, basé sur de nombreuses mesures expérimentales effectuées sur deux transformateurs à sec de 30 kVA, la méthode des pertes par excitation séparée et à courant nominal et la méthode en opposition sont comparées afin de déterminer leur comportement thermique et de valider les équations trouvée dans la norme IEEE C57.12.91 -2001.

La méthode des pertes par excitation séparée et à courant nominal

L'élévation de température est obtenue à partir de la méthode des pertes par excitation séparée et à courant nominal qui sera exploitée dans deux essais séparés: l'essai à circuit ouvert et l'essai en court-circuit. Après avoir mesuré l'augmentation de température pour chaque test, l'élévation totale de la température peut être calculée comme suit:

$$T_t = T_c[1 + \left(\frac{T_e}{T_c}\right)^{1.25}]^{0.8}$$

Où:

T_t: augmentation totale de la température d'enroulement avec un courant de charge dans les enroulements et l'excitation normale dans le noyau.

T_C: augmentation de température moyenne d'enroulements à la suite de l'essai d'échauffement avec un courant circulant dans un enroulement tandis que l'autre enroulement est court-circuité.

Te: L'augmentation de température moyenne mesurée suite à un échauffement avec excitation normale dans le noyau. Te est déterminée à partir d'un essai à tension et fréquence nominale du transformateur.

Cette méthode nécessite deux essais distincts, un à circuit ouvert à tension et fréquence nominale et l'autre en court-circuit au courant de charge nominal et fréquence nominale. Une fois la température stabilisée, les résistances d'enroulements à chaud sont mesurées afin de déterminer l'élévation de température de chaque essai. À la suite de ces deux essais, l'élévation de température totale de chaque unité peut être calculée.

L'élévation de température due aux pertes d'excitation est déterminée en mesurant la résistance des enroulements à la fin de l'essai en circuit ouvert. Normalement, le test en circuit ouvert est de 24 heures à tension et fréquence nominale, afin de permettre une stabilisation de la température du noyau.

Selon la norme IEEE Std C57.123 2002 [3], les exigences relatives à la mesure des pertes d'excitation sont les suivantes:

- La tension est égale à la tension nominale.
- La fréquence est égale à la fréquence nominale.
- Les mesures sont reportées à la température de référence.

Chaque fois que le signal appliqué contient des distorsions, la mesure doit être corrigée pour une onde de tension sinusoïdale.

L'élévation de température due aux pertes en charge est déterminée en mesurant la résistance d'enroulement à la fin de l'essai de court-circuit. Selon la norme IEEE C57.12.91-2001 [1], quelques mesures préparatoires doivent être respectées pour obtenir des résultats satisfaisants :

a) afin de déterminer la température des enroulements avec précision les conditions suivantes sont nécessaires :
   1) la température des enroulements doit être stabilisée,
   2) la température des enroulements doit être prise tout de suite avant et après l'essai de la même façon que celle décrite à la section 1.2.1. La moyenne entre les deux valeurs étant la vraie valeur pour la température des enroulements,
   3) la différence entre la température avant et après l'essai ne doit pas dépasser 5°,

b) les conducteurs utilisés pour court-circuiter le secondaire doivent avoir la section d'au moins la même dimension que les câbles utilisés pour raccorder les enroulements secondaires du transformateur,

c) la fréquence de la source utilisée pour mesurer les pertes dues à la charge doit avoir une incertitude de $\pm 5\%$.

La méthode en opposition

La méthode en opposition est une méthode de base pour tester les transformateurs à sec qui peut être utilisée lorsque plus d'un transformateur est disponible. Elle est souvent appelée méthode dos à dos. L'augmentation totale de la température d'enroulements peut être déterminée par cette méthode.

Dans notre cas, les deux transformateurs de 30 kVA ont la même tension et la même puissance. Les enroulements primaires (P1, P2) des deux transformateurs, T1 et T2, sont montés en parallèle et les enroulements secondaires (S1, S2) sont montés en série. Une source de tension V1 est connectée aux enroulements primaires (P1, P2) pour fournir à tension et fréquence nominale, le courant d'excitation total et les pertes par excitation de T1 et T2.

De l'autre côté, une source V2 fournit le courant de charge spécifié du secondaire (S1, S2) et les pertes cuivre des deux transformateurs. Dans la méthode en opposition, le courant I_2 dans les enroulements secondaires peut être exprimée de la manière suivante:

$$I_2 = \frac{U_{s2}}{Z_1 + Z_2}$$

Où

U_{s2} : La tension de la source variable V2
Z_1 : L'impédance équivalente de T1
Z_2: L'impédance équivalente de T2

Dans notre cas, l'analyseur de puissance, Voltech PM-6000, est à la fois relié aux enroulements primaires et secondaires pour mesurer les tensions, les courants et les pertes de puissance. Les six transformateurs de courant sont utilisés pour réduire le courant à une valeur acceptable pour l'analyseur qui est limité à un maximum de 30 A.

Le système d'acquisition de données est utilisé pour enregistrer la lecture de température d'enroulement provenant des thermocouples.

0.7 CONLUSION

Plusieurs méthodes peuvent être utilisées pour déterminer l'élévation de température du transformateur. Dans ce projet, nous comparons les résultats de mesure de l'augmentation de température obtenue à partir de la méthode des pertes par excitation séparée et à courant nominal et la méthode en opposition.

Ainsi, les conclusions suivantes ont été obtenues:

L'équation $T_t = T_c[1 + \left(\frac{T_e}{T_c}\right)^{1.25}]^{0.8}$ de la norme ANSI / IEEE C57.12.91 - 2001, code d'essais normalisés pour la distribution de type à sec et transformateurs a été vérifiée et jugée exacte.

L'augmentation de température issue de la méthode des pertes par excitation à courant nominal et de la méthode en opposition a été validée et les deux méthodes peuvent être utilisées pour déterminer l'élévation de température d'un transformateur de type sec efficacement.

Le banc d'essai utilisé dans notre laboratoire a été validée et le montage expérimental jugé adéquat tel que prescrit par les normes.

L'efficacité des essais a été calculée selon la norme CSA-C802.2-06 sur les valeurs minimales d'efficacité pour les transformateurs à sec.

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NOMENCLATURE

A:	Core cross-section area (m2).
B_m :	The actual peak value of the flux density
DC	Direct current
Eoc:	Open-circuit voltage (V)
Esc:	Short circuit voltage (V)
Ip:	Primary side current (A).
Is' :	Referred secondary side current (A).
I_t:	The test current,
I_r:	The rated current,
Isc:	Short circuit current
Ioc:	Open-circuit current (A)
$L_{winding}$:	The inductance of the windings
N:	Numbers of turns in coil,
NL:	No-load loss in watts at 100% of the rated voltage and ambient temperature.
Poc:	Actual power losses (W)
Pfe:	Power losses in the core (W)
Pc :	The corrected (reported) value of no load loss
Pm :	The measured value of no load loss,
Pr:	I^2R losses.
Ps:	Stray losses and eddy current losses.
Pco:	The no-load losses corrected for waveform distortion.
Pnc:	The no-load losses corrected for waveform distortion and then to the reference temperature of 20°C
Pnc1:	The no-load losses, corrected for waveform distortion at temperature Tnm.
PL75:	Load losses in watts at 75°C.
Psc:	Power losses in the short circuit
Pr(T):	The I^2R losses at temperature T,watts

Ps(T):	The stray losses at temperature T, watts,
P(T):	The transformer load losses corrected to temperature T, watts,
Ra:	The apparent resistance. (Ω)
R_p:	Primary winding resistance (Ω)
R_{fe}:	Core-loss resistance (Ω)
R_s':	Referred secondary winding resistance (Ω)
R_{eq}:	Equivalent resistance
$R_{winding}$:	The true resistance of the windings
Rs :	The resistance at desired temperature Ts.
Rm:	The measured resistance at the temperature, $_{Tm}$,
Ta:	Ambient temperature corresponding to hot resistance, R,
To:	Temperature corresponding to cold resistance, Ro, (°C)
Tr:	Average winding temperature rise of a terminal pair (°C),
Tra :	The ambient temperature at rated kVA, normally $30^{\circ}C$.
Tnm:	The core temperature during the measurement of no-load losses.
Tm:	The core temperature at the time of test
Vp:	Primary side voltage (V).
Vs' :	Referred secondary side voltage (V).
Va :	The reading of the average-responding, rms-calibrated voltmeter,
Vr :	The reading of the true-rms-responding voltmeter
Xp:	Primary winding reactance (H)
Xφ :	Core magnetizing reactance (H)
Xs':	Referred secondary winding reactance (H)
Xeq:	Equivalent reactance
Zeq:	Equivalent impedance
φ_m :	The total core flux in lines (wb),

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CHAPITRE 1

INTRODUCTION

1.1 PURPOSE OF RESEARCH

A transformer is an electric device which has at least two coils (windings) on the same magnetic core and transfers energy from one circuit to another by means of a common magnetic field. In operation, real transformers will release heat as a byproduct due to the core losses and winding losses. If the temperature of each part in the transformer exceeds the maximum acceptable temperature, a fast degradation or even a catastrophic failure of the insulation may occur.

The temperature rise in a transformer depends on multi-factors such as ambient temperature, output current and type of the core. Considering all these parameters, temperature rise estimation is still a complicated procedure. Moreover, it is also not practical to connect the transformer to a load with full rated capacity at the end of the assembly process. Although this would directly simulate the transformer operating condition, the total input power would be dissipated in the load.

The load power, which is equal to the rated load of transformer, is much larger than the sum of the core losses and winding losses that are dissipated in the transformer. Furthermore, the electrical heating of the load would not contribute to transformer heating. Therefore, this makes the electrical power consumption to become excessive under the test and it does not have a practical application for routine testing at the factory.

According to the ANSI and IEEE standards, several temperature rise test loading methods can be used for different types of dry-type transformers. In this project, the excitation loss and rated current method and the loading back (opposition) method will be used to study the average winding temperature rise.

In the separated excitation loss and rated current method, the temperature rise of ventilated dry-type transformer is obtained from two separate tests: open circuit test and short circuit test. The total temperature rise measurement can be calculated as a result of the two tests. The loading back method, described in the IEEE test code [1], requires two transformers which are used for heat runs test of dry-type transformers to determine the total temperature rise.

The purpose of this work is to compare the performances of the two methods, the loading back method and the separate excitation loss and rated current method and to address some issues such as reliability and accuracy of the methods.

1.2 LITERATURE REVIEW

"A dry-type transformer is one, in which the insulating medium surrounding the winding assembly is a gas or a dry compound."[15] The 'temperature rise' test of dry-type transformer is performed in order to determine the temperature rise over ambient temperature.

The temperature rise is one of the main factors which affect transformer aging and the insulating materials. IEEE standard C57.12.01-1998 [2] established the limits of temperature rise for continuously operated transformers.

The hot spot temperature rise and the average winding-temperature rise above the ambient temperature should not exceed the values given in the table 1.1. These values are based on an average daily ambient temperature of 30 °C, with a maximum ambient temperature of 40°C.

Insulation system temperature class (°C)	Winding hot spot temperature rise (°C)	Average winding-temperature rise (°C)
130	90	75
150	110	90
180	140	115
200	160	130
220	180	150

Table 1.1: Limits of temperature rise for continuously rated dry-type transformer windings

The existence of the transformer temperature rise is due to the losses in the winding and in the core. A simple equivalent circuit is normally used to explain the behavior of a non-ideal transformer.

Figure 1.1 gives the conventional well-known equivalent circuit of a single-phase transformer.

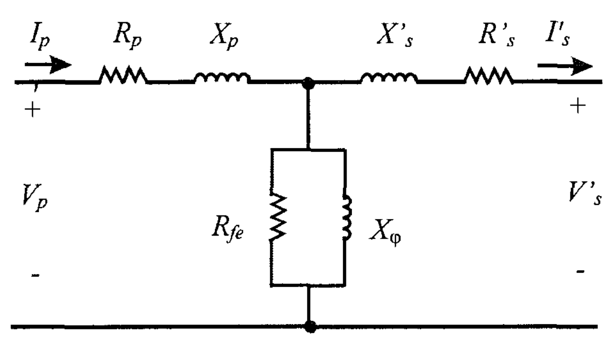


Figure 1.1: Equivalent circuit of single-phase transformer

Where:

R_p: Primary winding resistance (Ω)

X_p: Primary winding reactance (Ω)

R_{fe}: Core resistance (Ω)

X_φ: Core magnetizing reactance (Ω)

R_s': Secondary winding resistance referred to the primary (Ω)

X_s': Secondary winding reactance referred to the primary (Ω)

V_p: Primary voltage (V).

I_p: Primary current (A).

V_s': Secondary voltage referred to the primary (V).

I_s': Secondary current referred to the primary (A).

Winding resistances, core resistance and the magnetizing reactance saturation should be considered in the determination of the average winding temperature rise.

1.2.1 Ambient temperature measurement

Since the actual winding temperature is the sum of the ambient temperature and the temperature rise, ambient temperature is an important factor to determine the temperature rise. The actual ambient temperature is normally determined from thermometers suitably located in the testing area.

According to the IEEE Standard C57.12.91-2001 [1], the ambient temperature should not be less than 10°C or more that 40°C. In order to reduce the ambient temperature measurement errors, two factors should be considered:

A) The time lag between variations of the ambient temperature and the transformer temperature response;

B) The temperature variation due to the actual localization of the unit under test in the test area.

To solve the first problem, according to the IEEE Standard C57.12.91-2001 temperature sensors shall be placed in appropriate containers which includes such properties for the reason not to be less than 2 hours for the indicated temperature within the container to change 6.3 °C if suddenly placed in air that has a temperature 10 °C higher, or lower, than the previous steady-state indicated temperature within the container. [1].

And for the second problem, "the ambient temperature will be the average of readings from at least three temperature sensors spaced uniformly around the transformer under test. They should be located about one-half the height of the transformer and at a distance of 0.91−1.83 m from the transformer" [1].

1.2.2 Winding resistance measurement

It will be critical to have accurate measurement of the winding resistance in order to determine the load losses (I^2R losses) and also to the correct estimation of the temperature rise. In the determination of the temperature rise, the resistance measurement is done on all phases of each winding on the rated taps connection.

The winding resistance measurement includes two parts: the cold resistance measurement and the hot resistance measurement.

Cold resistance measurement

Normally cold-resistance measurements are taken on all phases of each primary and secondary winding on the rated taps before loading the transformer for heat run test. If there is difference between the cold resistance readings, the transformer should be cool at the ambient temperature to perform the cold resistance measurement after the loading test.

Before measuring the cold-resistance, we should determine the windings temperature as accurately as possible and the windings temperature should be recorded as the average reading of three thermocouples inserted between the coils. The thermocouples should be in actual contact with the surface of the windings. It should not be assumed that the ambient temperature is the same as the winding temperature.

However, to ensure the windings temperature is the ambient temperature, according to the standard C57.12.91-2001[1], the following recommendations should be respected before the cold resistance measurement:

A) All the thermal sensors at winding temperature and the surface measurement should not be more than 2°C, different from ambient temperature.

B) Ambient temperature in laboratory must not be changed more than 3°C for at least 3 hours before testing.

C) The transformer has been in a draft-free area for 24 hours and neither voltage nor current has been applied to it for 24–72 hours, depending on its size.

The cold-resistance measurement is normally performed using the bridge method or voltmeter-ammeter method. A test circuit for the measurement of winding resistance is shown in figure 1.2. A dc source is used to supply the steady direct current in the transformer winding to be measured. The maximum direct current which is used should not exceed 15% of the rated current of the winding being measured to avoid inaccuracy due to temperature and resistance increase cause by excessive dc losses. Readings taken on the voltage and the current across the winding should not be taken until the current and voltage have reached their steady-state value. The value of the winding resistance is determined by applying on Ohm's law to these readings.

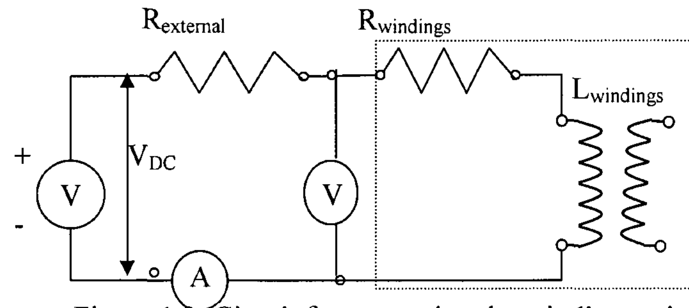


Figure 1.2: Circuit for measuring the winding resistance

In the winding resistance measurement, if a dc voltage source is applied to generate a dc current through the transformer windings, the initially apparent resistance will be larger than the true resistance value. It is possible for the true resistance, the apparent resistance, and the inductance of windings to change by time, and the relation of these values are expressed as follows:

$$R_a = \frac{V}{I} = R_{winding} + \frac{L_{winding}}{I} \times \frac{dI}{dt} \tag{0.1}$$

where:

R_a: The apparent resistance.
$L_{winding}$: The inductance of the windings
$R_{winding}$: The true resistance of the windings

From the equation 1.1 we can notice that the apparent resistance, R_a, is higher than the true resistance, $R_{winding}$, during the transient period and that the apparent resistance derived from the voltmeter and ammeter readings equals the true resistance only after the transient has subsided. Typical curves of voltage, current, and apparent resistance are shown in the figure 1.3. From this figure we can find the period of the transient is about 3 minutes.

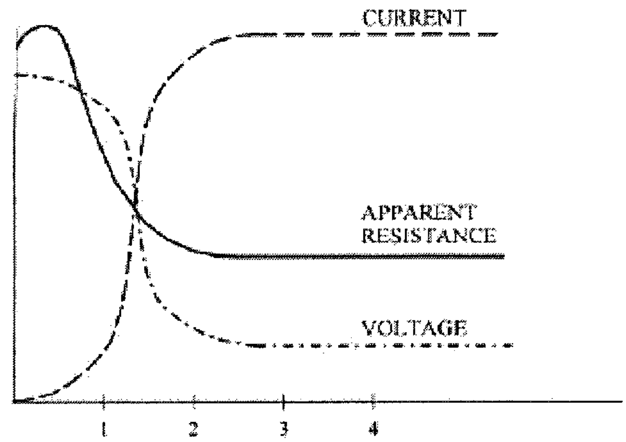


Figure: 1.3: Current, voltage and apparent resistance with time. [15]

Normally, when a dc voltage is applied, the current through the transformer winding rises slowly. The initial rise is proportional to the R-L time constant of the winding. The initial high impedance results from the effective inductance of the winding due to its iron core.

To avoid these measuring errors dc current sources are used instead of the voltage sources to determine the resistance. Moreover, for the range of dry-type transformers that can be tested in the laboratory, i.e. 10 to 200 kVA, the time constant is much shorter than the time constant of units with capacity exceeding hundred of MW.

Furthermore, in the hot resistance measurement at the end of short-circuit test, the cables connecting the transformer to the low-voltage source and the short-circuit connections must be rapidly removed and the small dc current sources and measuring leads should be reconnected before any resistance measurement can be done. Few minutes are necessary to do so. The transient period due to the winding time constant are usually completed before the first resistance measurement.

Hot resistance measurement

Hot resistance is measured after the transformer winding temperature is stabilized i.e. “variation of the winding temperature should not be more that 2 °C during a consecutive 3 hours period” [1]. Readings are taken on all windings of each phase and a cooling down curve is drawn for each winding of each phase. The first measurement on each phase should be taken as quickly as possible after the instant of shutdown power supply; the first resistance measurement of the winding phase used for the cooling curve must be taken within 6 minutes of the end of the test.

The sequence of the hot resistance measurements at shutdown for three-phase delta and wye connected transformers recommended from IEEE Standard C57.12.91-2001 is as follows:

a) One secondary resistance measurement on each of three secondary terminals X1-X2, X2-X3, and X3-X1. For wyes-connected low voltages, resistance at X1-X0, X2-X0, and X3-X0 terminals may be taken.

b) One resistance measurement on each of three primary terminals H1-H2, H2-H3, and H3-H1. For wyes-connected high voltages, resistance at H1-H0, H2-H0, and H3-H0 may be taken. The three secondary resistance measurements and one primary resistance measurement should be taken within 6 min.

c) To provide data to plot a resistance time cooling curve, take three additional measurements spaced at least 1 min apart on the primary terminals measured first under step b).

d) To provide data to plot a resistance-time cooling curve, take three additional measurements spaced at least 1 min apart on the secondary terminals measured first under step a).

e) Additional resistance measurements may be taken to improve the accuracy of the resistance time plot.

In our case, the measuring apparatus allowed the resistance of each winding to be obtained simultaneously. An automatic data recording system allows the resistance of each winding to be measured each 10 seconds. Therefore, the precedent procedure was not used. But there is still a time interval between the power shutdown and the instant of the first resistance measurement. To achieve an accurate hot resistance determination, the shutdown time is noted and the resistance cooling curve is extrapolated back to the instant of shut down using a standard curve fitting technique. .

1.2.3 Conversion of the resistance measurement

Transformer winding resistance is measured at various ambient temperatures. The resistance measurements are converted to a standard reference temperature. According to the IEEE/ANSI standard C57.12.91-2001 the conversions are obtained using the following formula:

$$\frac{R_s}{R_m} = \frac{T_s + T_k}{T_m + T_k} \tag{0.2}$$

Where

R_s : The resistance at desired temperature T_s.

R_m: The measured resistance at the temperature T_m,

T_s: The desired reference temperature.

T_m: The temperature at which resistance was measured.

T_k: 234.5 °C for copper, 225 °C for aluminum.

1.2.4 Calculation of the average winding temperature rise

The average temperature rise is determined by the cold-resistance and the hot-resistance. The cold resistance is measured at ambient temperature and the hot resistance will be determined after the heat run test. The equation 1.3 and 1.4 given below are used to determine the average winding temperature *T*.

$$T = \frac{R}{R_0} \times \left(T_k + T_o\right) - T_k \qquad (0.3)$$

or

$$T = \frac{\left(R - R_0\right)}{R_0} \times \left(T_k - T_0\right) + T_0 \qquad (0.4)$$

The average winding temperature rise is calculated by the following equation:

$$T_r = T - T_a \qquad (0.5)$$

Where,

T: Average winding temperature of a terminal pair corresponding to hot resistance, *R*,

R_o: Cold resistance of a terminal pair determined in accordance with the rules in this standard,

T_o: Temperature (°C) corresponding to cold resistance, R_o,

T_r: Average winding temperature rise of a terminal pair (°C),

T_a: Ambient temperature corresponding to hot resistance, R,

R: Hot resistance of a terminal pair,

T_k: 234.5 °C for copper,

225 °C for aluminum.

1.2.5 Correction for ambient air temperature

If the ambient temperature at the end of the test is different from the reference temperature T_{ra} (usually 30°C) hence the average winding temperature rise can be corrected by the following equation:

$$T_{c1} = T_r \times \left[\frac{(T_r + T_k + T_{ra})}{(T_r + T_k + T_a)} \right]^n \qquad (0.6)$$

where,

T_{c1}: The average winding temperature rise corrected for ambient temperature always at $30^\circ C$

T_{ra}: The ambient temperature at rated kVA, normally $30^\circ C$.

n: 0.7 for the sealed or non ventilated units ,

0.8 for ventilated self cooled.

1 for ventilated forced air.

1.2.6 Correction for test current different from rated current

When the test current is different from the rated current, the average winding temperature rise is corrected by using the following equation:

$$T_{c2} = T_{c1}(I_r / I_t)^{2n} \qquad (0.7)$$

Where

T_{c1}: The average winding temperature rise corrected for ambient temperature always at $30^{\circ}C$

T_{c2}: The average winding temperature rise corrected for rated current, °C

I_t: The test current,

I_r: The rated current

n: 0.7 for the sealed or non ventilated units ,
0.8 for ventilated self cooled.
1 for ventilated forced air.

1.3 DISSERTATION OVERVIEW

This master dissertation is composed of 5 chapters arranged as follows:

Chapter 1 Explanation of the important and objective point in this research project, discussion of the thermal behavior of dry-type transformer and general description of the test conditions.

Chapter 2 Analysis of the core losses and the winding losses and calculation of the total temperature rise from the separate excitation loss and rated current method.

Chapter 3 Loading back method, description of the laboratory experimental test set-up and calculation of the temperature rise from this method.

Chapter 4 Results for temperature rise, comparison and analysis of the average temperature rise obtained from the two methods.

Chapter 5 Conclusions and recommendations for future works.

CHAPITRE 2

THE TEMPERATURE RISE OBTAINED FROM THE SEPARATE EXCITATION LOSS AND RATED CURRENT METHOD

Introduction

The temperature rise is obtained from separate excitation loss and rated current method which requires open-circuit test and short-circuit test. After the temperature rise measured from each test, the total winding temperature rise can be calculated as follows:

$$T_t = T_c[1 + \left(\tfrac{T_e}{T_c}\right)^{1.25}]^{0.8} \tag{2.1}$$

Where:

T_t: Total winding temperature rise with load current in the winding and normal excitation in the core.

T_c: The average winding temperature rise measured at the end of the heat run test with load current flowing in one winding while the other winding being short-circuited. If the test current is different from the specified current or the ambient temperature is different from the reference temperature 30 °C, then it is advised to be corrected by using the equation 1.6 and 1.7.

T_e: The average winding temperature rise measured at the end of the heat run with normal excitation applied to the core at rated voltage and frequency.

Two tests are required: one is an open circuit test at nominal voltage and nominal frequency and the other is a short circuit test at specified load current and nominal frequency. After the winding temperature is stabilized, the hot winding resistances are instantly measured in order to determine the temperature rise from each test. As a result of the two tests, the total temperature rise of each unit can be calculated.

The main objective of this chapter is to analyze the core and winding losses, using equation (2.1) to calculate the total temperature rise from the separate excitation loss and rated current method.

2.1 EXCITATION LOSSES AND THE OPEN CIRCUIT TEST

A transformer dissipates excitation loss when is energized at constant voltage. This power loss constitutes a significant operating cost during the lifetime of transformers. The excitation loss includes two main components: hysteresis losses and eddy current losses. Excitation losses are often referred as core losses or no-load losses.

While transformer is connected to an ac power supply, there is a current that flows in its windings. The current flowing in the primary winding is a direct consequence of the flux existing in ferromagnetic core which consists of two components:

- Magnetization current I_φ, which is the current required to maintain the flux circulation in the core.

- Core-loss current I_{fe}, which is the current required to provide hysteresis and eddy current losses .

The sum of the magnetization current and the core-loss current in the core is called the excitation current. It can be expressed as follows:

$$I_{ex} = I_{\varphi} + I_{fe}$$

Figure 2.1 represents the standard equivalent circuit of single-phase transformer under open-circuit conditions.

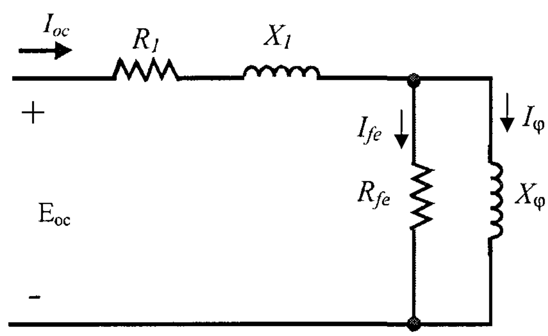


Figure 2.1: Equivalent circuit of single-phase transformer under open circuit test

Where:

R_{fe}:	Core-loss resistance (Ω)
X_{φ}:	Magnetizing reactance (Ω)
R_1:	Primary winding resistance (Ω)
X_1:	Primary winding reactance (Ω)
I_{oc}:	The no-load current (A)
I_{fe}:	The core-loss current (A)
I_{φ}:	The magnetization current (A)

The no-load losses, P_{oc}, are equal to the losses in the core and the windings. Since in the open-circuit test, the winding loss is very small, these losses can be negligible. Therefore, with this assumption, P_{fe} and P_{oc} are the same. E_{oc} is the sum of the excitation voltage E_{ex} and the voltage dropped across the winding resistance. Since the winding losses are very small compared to the core losses, the E_{oc} is considered as the excitation voltage, E_{ex}. Hence we can calculate R_{fe} and X_{φ} by the following equations.

Single-Phase and **Three-Phase**

$$\begin{cases} \cos\theta = \dfrac{P_{fe}}{E_{ex}I_{ex}} \approx \dfrac{P_{oc}}{E_{oc}I_{oc}} \\ R_{fe} = \dfrac{P_{fe}}{I_{fe}^{2}} = \dfrac{E_{oc}}{I_{oc}\times\cos\theta} \\ X_{\phi} = \dfrac{E_{oc}}{I_{oc}\times\sin\theta} \end{cases} \qquad \begin{cases} \cos\theta = \dfrac{P_{fe}}{E_{ex}I_{ex}} \approx \dfrac{P_{oc}}{3\times E_{oc}I_{oc}} \\ R_{fe} = \dfrac{P_{fe}}{I_{fe}^{2}} = \dfrac{E_{oc}}{3\times I_{oc}\times\cos\theta} \\ X_{\phi} = \dfrac{E_{oc}}{3\times I_{oc}\times\sin\theta} \end{cases} \tag{2.2}$$

where:

E_{oc}	:	Open-circuit voltage (V)
I_{oc}	:	Open-circuit current (A)
P_{oc}	:	Actual power losses (W)
P_{fe}	:	Power losses in the core (W)
R_{fe} and X_{φ}	:	Resistance and reactance of the core (Ω)

2.1.1 Determination of the hysteresis losses and eddy current losses

When a transformer is energized, there is some power lost in the core. These losses can divided in two main components:

- Hysteresis losses, which are caused by the cyclic reversal of flux in the magnetic circuit.
- Eddy current losses, which are caused by eddy or induced currents circulating within the steel induced by the flow of magnetic flux normal to the width of the core.

For a given core material, hysteresis loss is proportional to the frequency, and is a function of the peak flux density to which it is subjected. The total hysteresis losses for a specific volume at a frequency f can be expressed:

$$P_h = k_h \times f \times B_m^n$$

The eddy current losses are proportional to the square of the frequency and the square of the peak flux density. For a given volume of magnetic material, a given lamination thickness and a given frequency f, the equation of eddy current losses is as follows:

$$P_e = k_e \times f^2 \times B_m^2$$

The total core losses are the sum of the hyteresis losses and the eddy current losses and can be expressed as following:

$$P_{fe} = P_h + P_e = k_h \times f \times B_m^n + k_e \times f^2 \times B_m^2$$

where:

k_h and k_e : Constants of the magnetic material

f : The frequency,

B_m : The actual peak value of the flux density

n: Steinmetz coefficient (approximately 2, for usual modern steels)

If the total core losses equation is divided by the frequency, then:

$$\frac{P_{fe}}{f} = k_e \times f \times B_m^2 + k_h \times B_m^n$$

According to the Faraday's law and the basis of the transformer operation, the voltage induced in the coils:

$$e = N \times \frac{d\varphi}{dt} = 2\pi \times N \times f \times \varphi_m \times \cos(\omega t)$$

When $\qquad \cos(\omega t) = 1 \Rightarrow E_{\max} = 2 \times \pi \times N \times f \times \varphi_m$

$$E_{rms} = \frac{E_{\max}}{\sqrt{2}} = \sqrt{2} \times \pi \times N \times f \times \varphi_m = 4.44 N \times f \times A \times B_m$$

Then E_{rms} can be written as:

$$E_{rms} = k \times f \times B_m$$

where $\qquad k = 4.44 N \times A$ and $k' = 1/k$

and $\qquad B_m = k' \times \left(E_{rms}/f \right)$

where N, φ_m and A are :

N: Numbers of turns in coil,

φ_m : The total core flux in lines (wb),

A: Core cross-section area (m^2).

In fact the core losses depend on the hysteresis component which varies linearly with the frequency while the eddy current component varies linearly with the square of frequency. If the ratio of $\frac{E}{f}$ is constant, the peak flux density remains the same and the relation for $\frac{P_{fe}}{f}$ is:

$$\frac{P_{fe}}{f} = k_e' f + k_h'$$

and $$\frac{P_h}{f} = k_h',$$

$$\frac{P_e}{f} = k_e'$$

The above equations define a straight-line which intercepts on the vertical axis equal to the hysteresis loss k_h', and the slope of the line is the coefficient of f, k_e', as shown in figure 2.2

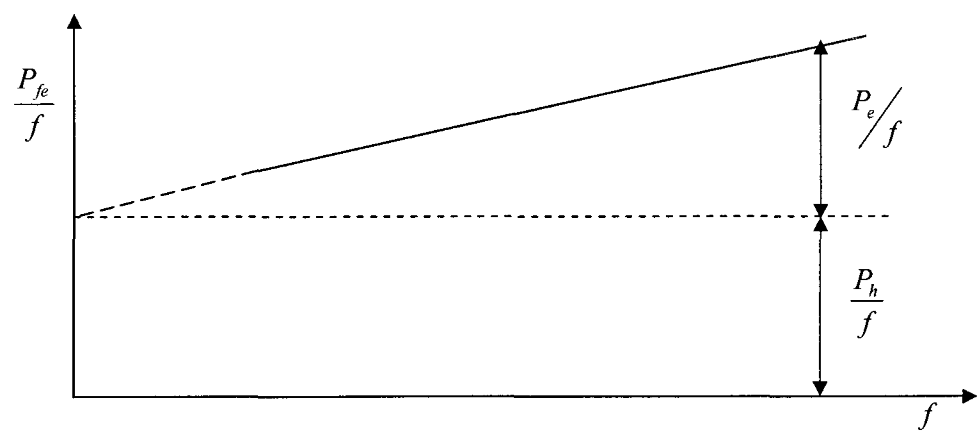


Figure 2.2: Curve of $\frac{P_{fe}}{f}$ as a function of frequency with constant $\frac{E}{f}$

2.2 TEMPERATURE RISE MEASURMENT FOR THE EXCITATION LOSSES ANSI/IEEE C57.12.91-2001 [1]

The temperature rise due to excitation loss is determined by measuring the winding resistance at the end of the open circuit test. Normally, the open circuit test lasts 24 hours at nominal voltage and rated frequency in order to let the core temperature stabilize.

According to the IEEE Std C57.123-2002[3], the requirements for excitation loss measurement are as follows:

- Voltage is equal to the rated voltage.
- Frequency is equal to the rated frequency.
- Measurements are reported at the reference temperature.
- Whenever the applied waveform is distorted, the measurement must be corrected to a sinusoidal voltage waveform.

2.2.1 Measuring circuitry for open-circuit test

The connections for no-load losses test of a single-phase transformer is given in figure 2.3.

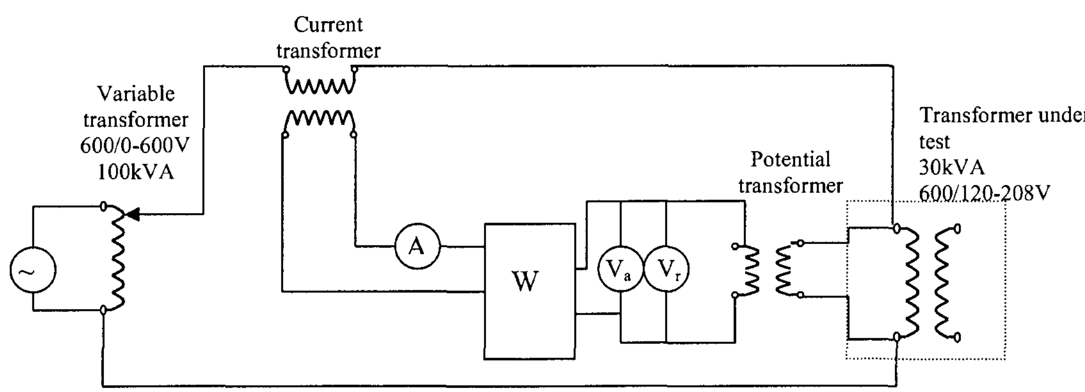


Figure 2.3: Test circuit for no-load losses measurement of single-phase transformer

In the figure 2.3, the instruments are as follows:

A : Ammeter,

W : Wattmeter,

V_a : An average-responding, root mean square(rms) calibrated voltmeter,

V_r : A true root mean square(rms) voltmeter.

In no-load losses measurement, the average-voltage voltmeter method is used which is the most accurate as the no-load losses are based on a sine-wave voltage. This method uses two voltmeters connected in parallel. One voltmeter labeled V_a represents an average- responding, rms-calibrated voltmeter. The other voltmeter labeled V_r represents a true rms-responding voltmeter. The corrections are discussed later.

In our case, the connection for no-load loss test of a three-phase transformer is shown in figure 2.4. The primary windings are supplied by a variable transformer at nominal voltage 600V, and the secondary left open. The power analyzer, Voltech PM-6000, is connected to the primary and is measured the following parameters: rms and fundamental voltages, rms and fundamental no-load currents, power and power factor.

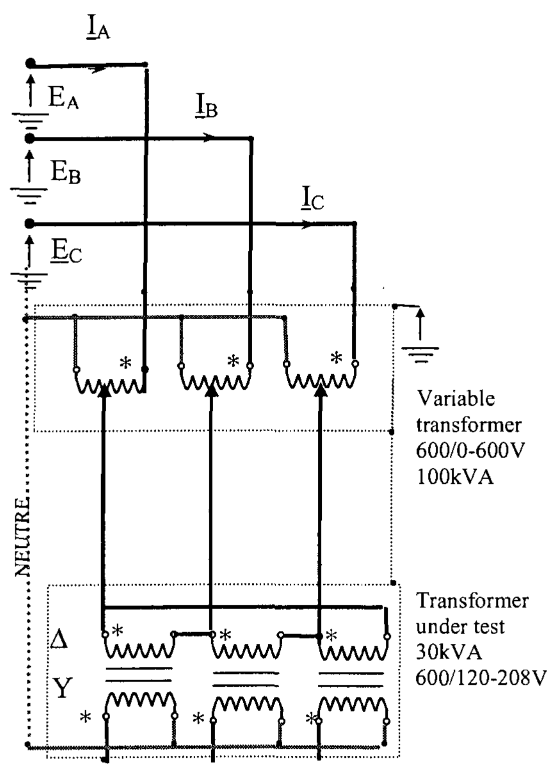


Figure 2.4: Test circuit for no-load losses measurement of three-phase transformer

2.2.2 Waveform correction of no-load losses [1]

In the open-circuit test, impressed voltage harmonics cause the rms waveform value to become different from the average-absolute (rms-scaled) value. The no-load losses correction is corrected to a sine-wave by a formula given from the IEEE test code [1], using the average-voltage voltmeter method.

The correction is shown as follows.

$$P_c(Tm) = \frac{P_m}{P_1 + \left(\frac{V_r}{V_a}\right)^2 \times P_2}$$

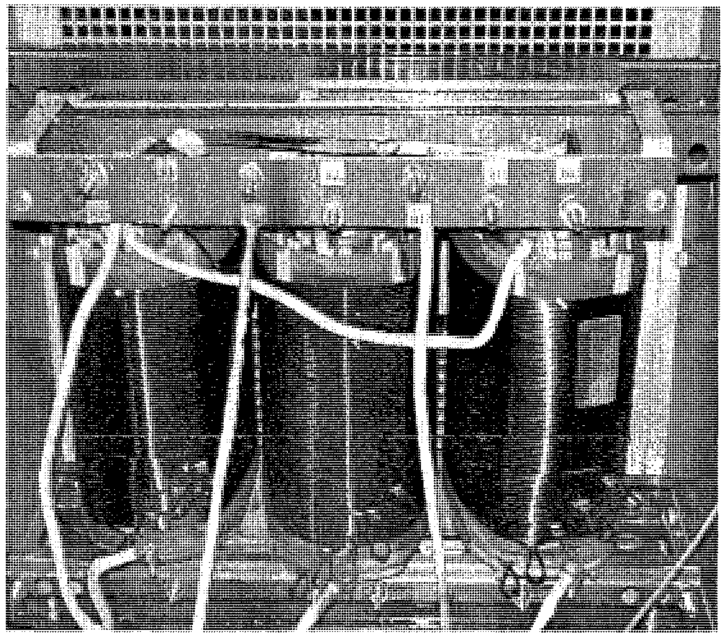
Where:

- T_m: The core temperature during the test
- P_c : The corrected value of no-load loss
- P_m : The measured value of no-load loss,
- V_a : The reading of the average-responding, rms-calibrated voltmeter,
- V_r : The reading of the true-rms-responding voltmeter
- P_1 : The per-unit hysteresis losses
- P_2 : The per-unit eddy-current losses

According to the ANSI/IEEE C57.12.91-2001 [1], if the actual two values, P_1 and P_2 are not available, it is suggested that the two losses components be equal in values, assigning each a value of 0.5 p.u. Since the power analyzer can directly measure the fundamental power, the use of the previous method is avoided.

2.3 EXPERIMENTAL RESULTS FOR OPEN CIRCUIT TEST

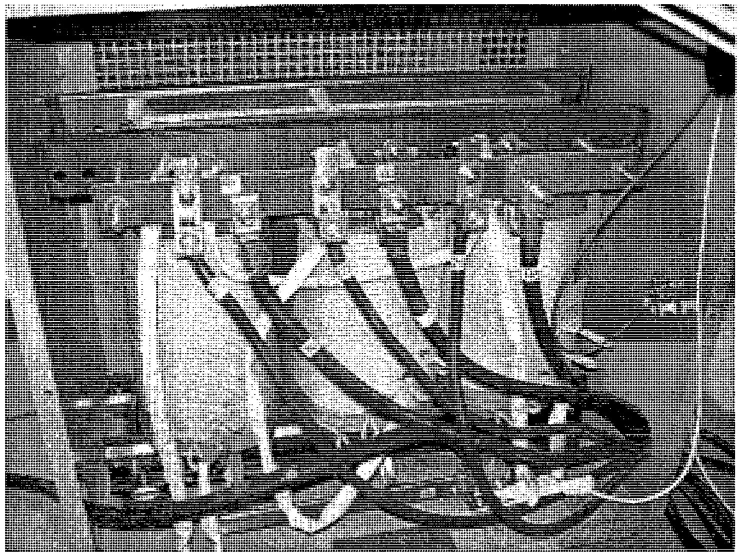
In the laboratory, two dry-type distribution transformers are tested. One winding is copper and the other one is aluminum. The primary windings of the transformers are delta connections and the nominal voltage is 600V while the secondary windings are wye connections and the voltage is 120V/208V. The pictures of the aluminum and the copper transformers and their nameplates are given in figures 2.5 and 2.6.



A) Copper transformer

B) The nameplate of the copper transformer

Figure 2.5: copper transformer and its nameplate



A) Aluminum Transformer

B) The nameplate of the aluminum transformer

Figure 2.6: Aluminum transformer and its nameplate

2.3.1 Determination of the parametres R_{fe} and X_{φ}

The parameters measured in the no-load test are given as follows:

Parameters	Aluminum transformer	Copper transformer
P_{oc} (w)	221.5	203.9
E_{oc} (V)	599.9	600
I_{oc} (A)	1.4	1.2

Then , R_{fe} et X_{φ} can be calculated by the equation 2.2 and the results present as follows:

Aluminum Transformer:

$$\begin{cases} P_{oc} = 221.5W \\ E_{oc} = 599.9V \\ I_{oc} = 1.4A \end{cases} \Rightarrow \begin{aligned} &\cos\theta = \frac{P_{oc}}{3\times E_{oc} I_{oc}} = \frac{221.5}{3\times 599.9\times 1.4} \approx 0.088 \\ &\sin\theta \approx 0.996 \\ &R_{fe} = \frac{E_{oc}}{3\times I_{oc}\cos\theta} = \frac{599.9}{3\times 1.4\times\cos\theta} = 1623\Omega \\ &X_{\varphi} = \frac{E_{oc}}{3\times I_{oc}\sin\theta} = \frac{599.9}{3\times 1.4\times\sin\theta} = 143.4\Omega \end{aligned}$$

Copper Transformer:

$$\begin{cases} P_{oc} = 203.9W \\ E_{oc} = 600V \\ I_{oc} = 1.2A \end{cases} \Rightarrow \begin{aligned} &\cos\theta = \frac{P_{oc}}{3\times E_{oc} I_{oc}} = \frac{203.9}{3\times 600\times 1.2} \approx 0.094 \\ &\sin\theta \approx 0.995 \\ &R_{fe} = \frac{E_{oc}}{3\times I_{oc}\cos\theta} = \frac{600}{3\times 1.2\times\cos\theta} = 1773\Omega \\ &X_{\varphi} = \frac{E_{oc}}{3\times I_{oc}\sin\theta} = \frac{600}{3\times 1.2\times\sin\theta} = 167.5\Omega \end{aligned}$$

2.3.2 Winding resistance measurment

Cold resistance measurement

As described in the section 1.2.2, the *MEGGER AVO Multi-Amp 830280 Transformer Ohmmeter* is applied to measure the cold resistances of the two transformers.

The cold resistance of the aluminum transformer is measured at the ambient temperature 22.5°C, and the copper transformer is measured at 23.5°C. The values are shown in table 2.1.

Windings	R_{cold}	R_{cold}
	22.5°C	23.5°C
	Aluminum	Copper
Primary	mΩ	mΩ
R_{p1}	181.9	289.0
R_{p2}	181.0	289.0
R_{p3}	181.3	289.0
Secondary		
R_{s1}	8.5	10.0
R_{s2}	8.5	10.0
R_{s3}	8.5	10.0

Table 2.1: Cold resistance measurements

The R_{p1}, R_{p2} and R_{p3} are the resistances of primary windings and R_{s1}, R_{s2} and R_{s3} are the secondary windings resistances. R_{p2} and R_{s2} are located in the middle leg of the cores.

Hot resistance measurement

In the open circuit test, the primary windings of the transformer are supplied at the nominal voltage and the nominal frequency during 24 hours with the secondary open. Furthermore, experimental measurement indicates that the winding temperature rise obtained from open circuit is low and it has slow core cooling speed.

Therefore, the hot resistance may be measured by using the *MEGGER AVO Multi-Amp® 830280 Transformer Ohmmeter,* after shut down the power supply within 6 minutes.

In the open circuit test, the hot resistance of the aluminum transformer is measured at 24.5°C and the copper transformer is measured at 23.9°C. Corresponding values are shown in table 2.2.

Windings	R_{hot}	R_{hot}
	24.5°C	23.9°C
	Aluminum	Copper
Primary	mΩ	mΩ
R_{p1}	195.1	303.0
R_{p2}	195.4	305.0
R_{p3}	195.4	304.0
Secondary		
R_{s1}	9.5	10.8
R_{s2}	9.6	10.9
R_{s3}	9.5	10.9

Table 2.2: Hot resistances measurement from the open circuit test

2.3.3 The temperature rise calculation from the open circuit test

By measuring the cold and hot resistances from the open circuit test, the winding temperature rise is calculated, using equation 1.3, 1.4 and 1.5. The winding temperature rise is corrected for a reference temperature of 30 °C by using the equation 1.6. The results are shown in table 2.3.

Winding	Aluminum Transformer	
	T_{rise} at 24.5°C	T_{rise} corrected at 30°C
Primary	°C	°C
R_{p1}	16.0	16.2
R_{p2}	17.7	18.0
R_{p3}	17.2	17.5
Secondary		
R_{s1}	28.8	29.2
R_{s2}	31.7	32.2
R_{s3}	27.1	27.5

A) Aluminum transformer

Windings	Copper Transformer	
	T_{rise} at 23.9°C	T_{rise} corrected at 30°C
Primary	°C	°C
R_{p1}	12.1	12.4
R_{p2}	13.9	14.2
R_{p3}	13.0	13.3
Secondary		
R_{s1}	21.1	21.5
R_{s2}	23.7	24.1
R_{s3}	23.4	23.8

B) Copper transformer

Table 2.3: The average temperature rise corrected at 30 °C from open circuit test

Conclusions:

The temperature rise calculated from the excitation losses is normally from 10 °C to 30 °C. There is a temperature rise difference between the primary and secondary, because of the distance between the winding and core. Hence, the shorter the distance is, the higher the temperature rise. Moreover, the coils located on the middle leg, reach a slightly higher temperature.

2.4 LOAD LOSSES AND SHORT CIRCUIT TEST

The load losses dissipated by a transformer depend on the load connected to the secondary winding. Load losses are normally obtained from the short circuit test by applying a specified load current at the rated frequency to one winding while a short circuit is placed across the other side. In this case, the magnetizing impedance is assumed to be much larger than the winding resistances and leakage reactance and, therefore, is neglected.

The transformer load losses include two main parts:

a) The losses produced by I^2R due to load current in the winding impedance;

b) The stray losses in various metallic transformer parts due to eddy currents induced by leakage field.

But for small rated power dry-type transformers, the stray losses are normally very small, from 1 % to 2 % of the load losses.

The equivalent circuit of a single-phase transformer under the short circuit test is shown in figure 2.7.

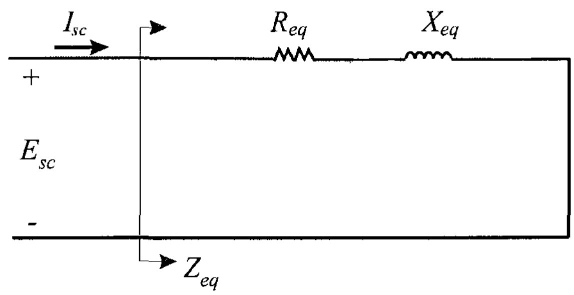


Figure 2.7: Equivalent circuit of single-phase transformer under short-circuit test.

Where

Z_{eq}: Equivalent impedance (Ω)

R_{eq}: Equivalent resistance (Ω)

X_{eq}: Equivalent reactance (Ω)

E_{sc}: Short circuit voltage (V)

I_{sc}: Short circuit current (A)

The equivalent impedance can be determined as follows:

Single-Phase	and	**Three-Phase**
$Z_{eq} = \frac{E_{sc}}{I_{sc}}$		$Z_{eq} = \frac{E_{sc}}{\sqrt{3} \times I_{sc}}$
$R_{eq} = \frac{P_{sc}}{I_{sc}^2}$		$R_{eq} = \frac{P_{sc}}{3 \times I_{sc}^2}$
$X_{eq} = \sqrt{Z_{eq}^2 - R_{eq}^2}$		$X_{eq} = \sqrt{Z_{eq}^2 - R_{eq}^2}$

The secondary impedance, R_2 and X_2 are referred to the primary side by multiplying the components by ratio "m" square, the equivalent impedance can be written as follows:

$$Z_{eq}=Z_1+m^2Z_2$$

$$R_{eq}=R_1+m^2R_2$$

$$X_{eq}=X_1+m^2X_2$$

For a normal transformer, R1 and m^2 R_2 should have similar values:

$$R_1 \approx m^2 R_2 .$$

It is normally assumed that R_1 and R_2 in alternating current have approximately the same ratio as in direct current [14]. Therefore:

$$\frac{R_{2ac}}{R_{1ac}} \approx \frac{R_{2dc}}{R_{1dc}} = \frac{R_2}{R_1}$$

$$R_{eq} = R_1 + m^2 R_2 = R_1 + m^2 R_1 ({R_{2sc}}/{R_{1sc}})$$

$$R_1 = \frac{R_{eq}}{1 + m^2 ({R_{2sc}}/{R_{1sc}})}$$

On the other hand, for a pair of winding, the leakage reactance of the primary and secondary are considered to be equal:

$$X_1 = X_2' = \frac{1}{2} X_{eq}$$

The base impedance Z_b can define either in terms of phase voltage, E_{ph} or line voltage, E_l, and S_{nom} is the nominal rating.

Single-Phase and **Three-Phase**

$$Z_b = \frac{E_l^2}{S_{nom}} \qquad Z_b = \frac{3 \times E_{ph}^2}{S_{nom}}$$

2.5 TEMPERATURE RISE MEASURED FOR LOAD LOSSES ANSI/IEEE C57.12.91-2001 [1]

The temperature rise due to load losses is determined by measuring the winding resistances at the end of the short circuit test. According to IEEE Standard C57.12.91-2001[1], the following preliminary requirements should be considered for accurate test results:

a) To determine the temperature of the windings with sufficient accuracy, the following conditions shall be met.:

1) The winding temperature of transformer must be stable.

2) The windings temperature shall be taken instantly before and after the load losses, similarly the impedance voltage test which is described in the ambient temperature determination in section 1.2.1. The average shall be taken as the true temperature.

3) Before and after the test the difference in ambient temperature shall not exceed 5°C.

c) The test source frequency used for measuring load losses and impedance voltage shall be within $\pm 5\%$ of the nominal value.

2.5.1 Measuring circuitry for open-circuit test

The connection of a single-phase transformer for the short circuit test is shown in figure 2.8. Single-phase Marcus transformer (step-down voltage 360/36V) is used to supply the primary of the transformer and the frequency of the source is at $60Hz$.

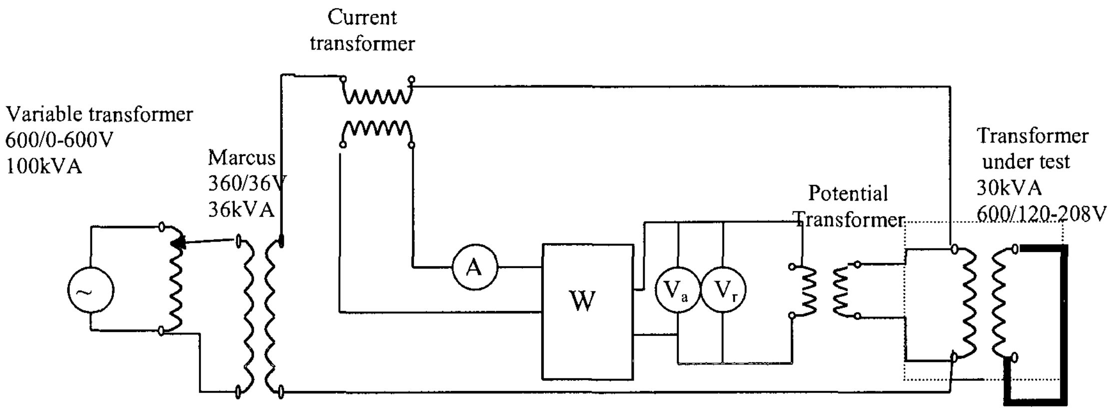


Figure 2.8: Test circuit for load losses measurement of single-phase transformer

In the figure 2.8, the instruments are as follows:

A : Ammeter,

W : Wattmeter,

V_a : An average-responding, root mean square(rms) calibrated voltmeter,

V_r : A true root mean square(rms) voltmeter.

The test circuit having three-phase transformer has the same connection as the single-phase transformer but with three sets of instruments. The measuring circuit for the three-phase transformer is shown in the figure 2.9. In our case, only a Voltech power analyzer, can emulate all the previous instruments.

The primary windings of the three-phase transformer are supplied by the three single-phase Marcus transformers to adjust the load current, and the secondary are short-circuited.

Once again a single power analyzer is connected to the three-phase transformer in order to measure the voltages, the power losses and the currents.

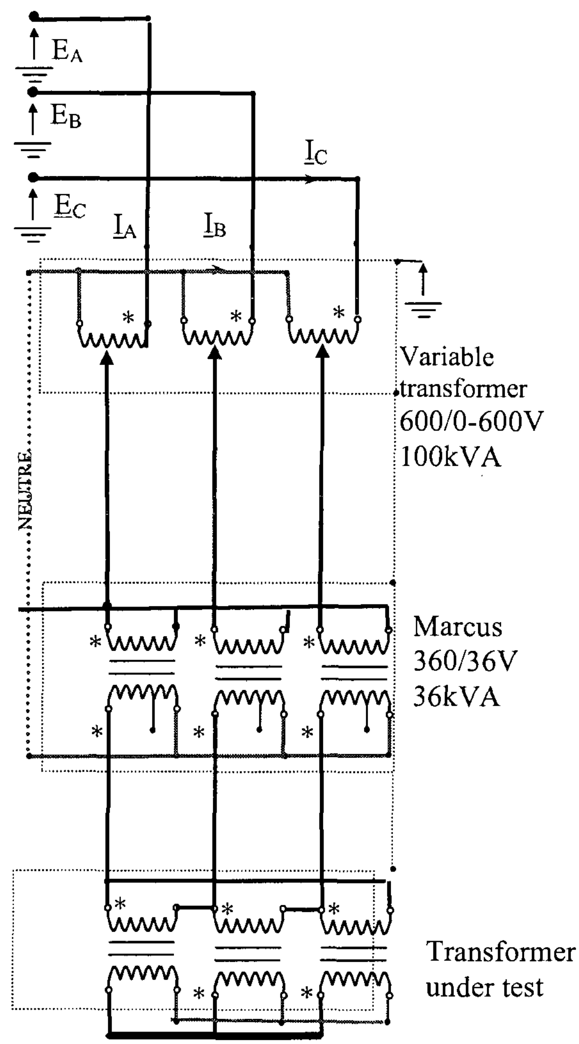


Figure 2.9: Test circuit for load losses measurement of three-phase transformer

After winding temperature has been stabilized, power supply is shut down and dc currents are injected in windings in order to measure the hot resistances. As a result the hot resistance is determined by using curve fitting to extrapolate hot resistance back to the instant of the power supply shutdown.

2.5.2 Hot resistance measurement

The circuitry to measure the hot resistances is shown in the figure 2.10. It composed two parts: the circuit of dc current injection and the circuit of hot resistances measurement.

In the figure, the left delta circuit is the primary windings of the transformer tested and the right wye circuit is the secondary windings. Three dc current sources (C1, C2 and C3) are used in the injection circuit. C1 injects to the primary windings, while C2 and C3 are used in the secondary windings. Six channels of a data acquisition system are used to record the hot resistances and the winding temperature at intervals of 10 seconds. Channel 1 to channel 6, respectively measure the primary windings resistances (Rp1, Pp2 and Rp3) and secondary resistances (Rs1, Rs2 and Rs3).

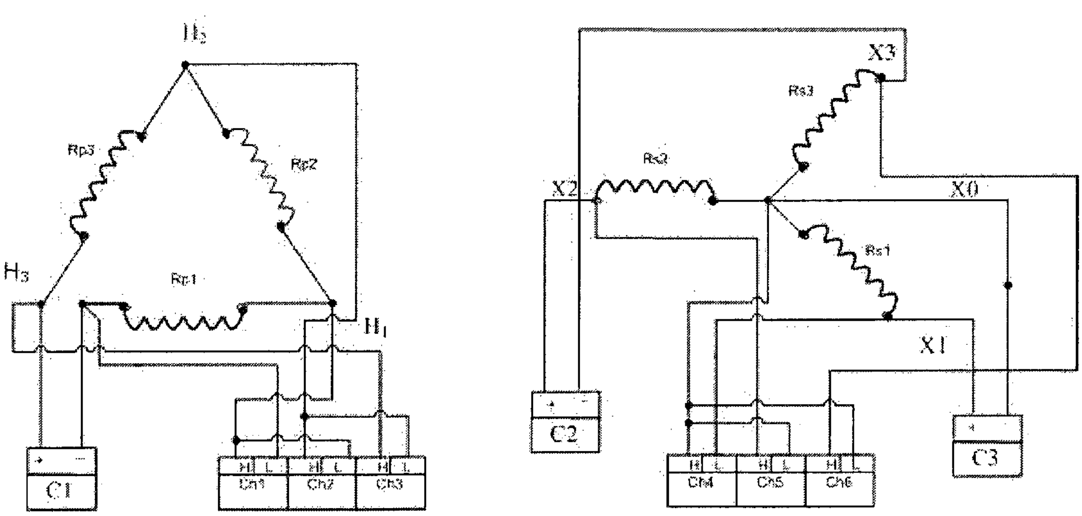
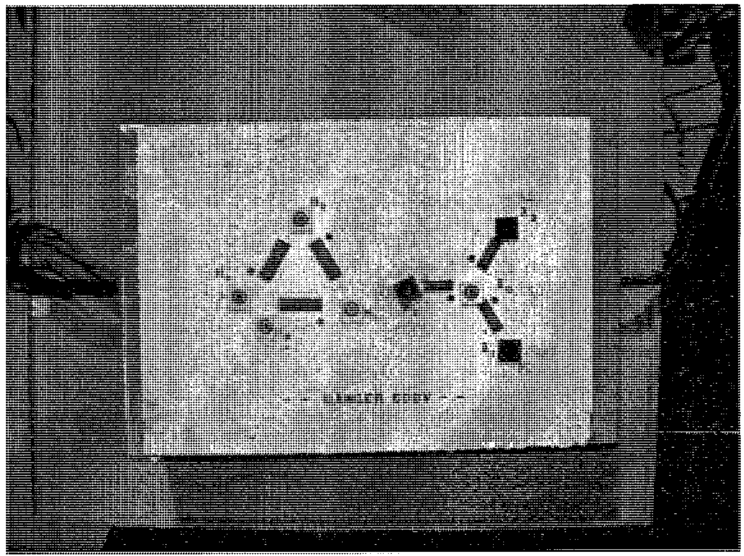
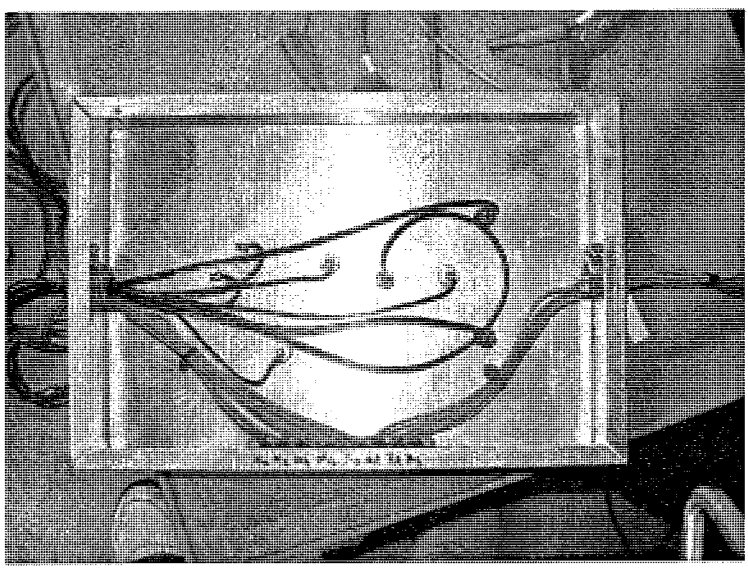


Figure2.10: Hot resistance measurement circuit

In the laboratory, a circuit board was fabricated to facilitate the connections of the dc supplies to the transformer primary and secondary windings and to the data acquisition system. The circuit board is shown in figure 2.11.



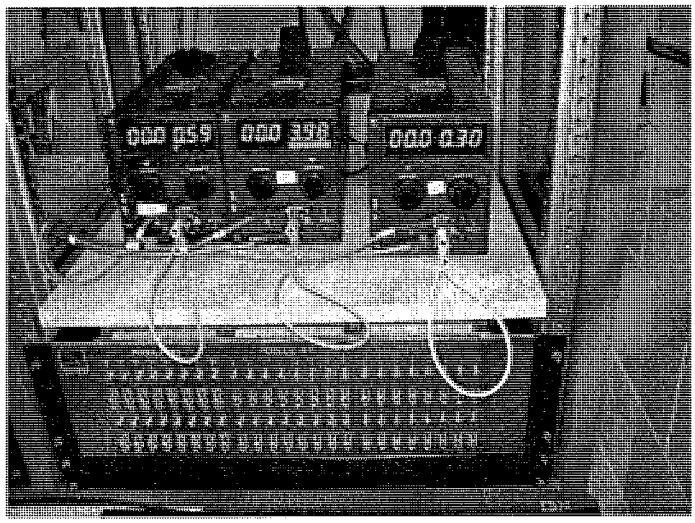
A) The front side of circuit board



B) The back side of circuit board

Figure 2.11: Circuit board

After the winding temperature is stabilized, the power supply is shut down. The dc current is injected into the circuit board to measure the hot resistances and the data acquisition system records the hot resistances. Figure 2.12 and figure 2.13 show the dc-power supplies and the circuit board during a typical hot resistance measurement.



2.12: Dc current Source

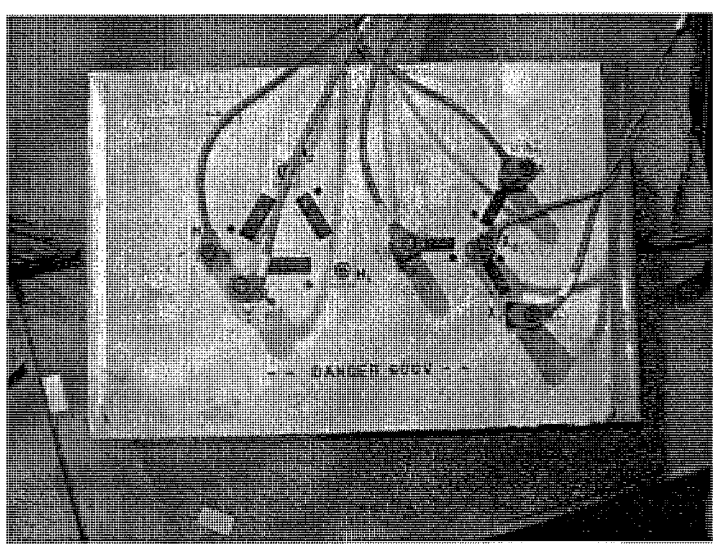


Figure2.13: The circuit board used under test

According to the ANSI / IEEE C57.12.91-2001 [1], the temperature variations in transformer windings must not exceed the permissible values. Thermocouples were selected to meet the UL 1561 standard; the size of the wire should neither be larger than the number AWG24 wire, nor smaller than the number AWG30 wire.

2.5.3 Temperature correction of load losses ANSI/IEEE C57.12.91-2001 [1]

The load losses(I^2R losses)and stray losses, of a transformer vary with temperature and should be corrected to a reference temperature.

The I^2R loss, $P_r(T_m)$, is equal to the square of the current multiplied by the value of winding resistance (corrected to the temperature, T_m, at which the measurement of load losses and impedance voltage was done). The stray losses, $P_s(T_m)$, of the transformer is equal to these I^2R losses subtracted from the measured load loss, $P(T_m)$. The equation can be expresses as follows:

$$P_s(T_m) = P(T_m) - P_r(T_m)$$

where:

$P_s(T_m)$: The calculated stray losses (watts) at temperature T_m,

$P(T_m)$: The transformer load losses (watts),at temperature T_m

$P_r(T_m)$: The calculated I^2R loss (watts) at temperature T_m

"The I^2R component of load losses increases with temperature, while the stray loss component decreases with temperature. Therefore, it will be desirable to convert the load losses from the temperature measured, T_m, to another reference temperature, T, the two components of the load losses are corrected separately."[1]

Thus:

$$P_r(T) = P_r(T_m)\frac{(T_k + T)}{(T_k + T_m)}$$

$$P_s(T) = P_s(T_m)\frac{(T_k + T_m)}{(T_k + T)}$$

then

$$P(T) = P_r(T) + P_s(T)$$

where:

$P_r(T)$:	The I^2R losses at temperature T,watts
$P_s(T)$:	The stray losses at temperature T, watts,
$P(T)$:	The transformer load losses corrected to temperature T, watts,
T_k :	234.5 $^\circ C$ for copper,
	225 $^\circ C$ for aluminum.

2.6 EXPERIMENTAL RESULTS FOR SHORT CIRCUIT TEST

In the short circuit test, the nominal load current of the transformers under test, I_n can be expressed as follows:

$$I_n = \frac{S_n}{\sqrt{3} * E_{ll}} = \frac{30000VA}{\sqrt{3} * 600V} \approx 28.87A$$

The load current in a real transformer is varied by the load impedance, normally from 50% to 100% of the nominal current. In our case, the short circuit tests is done for 6 values of load current, from 50% to 100% increasing by step of 10% of the nominal load current by adjusting the variable transformer.

2.6.1 Determination of the equivalent impedance Z_{eq}

In the short circuit test, the equivalent impedance of transformers can be calculated from the current I_{sc}, the voltage E_{sc} and the power loss P_{sc} using the following equations:

$$R_{eq} = \frac{P_{sc}}{3 \times I_{sc}^2}$$

$$Z_{eq} = \frac{E_{sc}}{\sqrt{3} \times I_{sc}}$$

$$X_{eq} = \sqrt{Z_{eq}^2 - R_{eq}^2}$$

Table 2.4 shows the values of the winding impedance and load losses of the two transformers.

Load current [A]		Aluminum transformer							
		E_{sc}[V]	Load losses[W]	Impedance(Ω)			Impedance (%)	Ambient Temperature (℃)
				R_{eq}	X_{eq}	Z_{eq}		
50%I_n	14.5	8.4	129.9	0.206	0.264	0.334	2.79	23.5
60%I_n	17.3	10.1	190	0.212	0.262	0.337	2.81	24.5
70%I_n	20.2	12.0	270.9	0.221	0.262	0.343	2.86	25.0
80%I_n	23.2	13.9	363.2	0.225	0.263	0.346	2.88	25.5
90%I_n	26.1	15.8	473.8	0.232	0.262	0.350	2.91	25.8
100%I_n	28.85	17.8	600.3	0.240	0.263	0.356	2.97	27.0

A) Aluminum transformer

Load current [A]		Copper transformer						
		E_{sc}[V]	Load losses [W]	Impedance(Ω)			Impedance (%)	Ambient Temperature (℃)
				R_{eq}	X_{eq}	Z_{eq}		
50%I_n	14.4	9.2	175.3	0.282	0.238	0.369	3.07	24.5
60%I_n	17.3	11.2	262.5	0.292	0.233	0.374	3.11	24.5
70%I_n	20.2	13.3	364	0.297	0.237	0.380	3.17	24
80%I_n	23.2	15.7	502	0.311	0.237	0.391	3.26	26
90%I_n	26.1	17.9	650.5	0.318	0.236	0.396	3.30	25.5
100%I_n	28.8	20.3	825.8	0.332	0.236	0.407	3.39	26.5

B) Copper transformer

Table 2.4: Impedance and load losses for different load currents

2.6.2 Load losses correction of temperature

As mentioned in section 2.5.1, I^2R losses (P_r) and stray losses (P_s) of a transformer varied with temperature, and they should be corrected at a reference temperature, 30°C.

The following example shows the temperature correction for the full load case. Values obtained from the power analyzer and the data acquisition system are:

$$I = 28.8A$$
$$R = 0.332\Omega$$
$$T_m = 26.5^{\circ}\mathrm{C}$$
$$P_{sc} = 825.8W$$

$$\mathrm{P_r}(26.5) = \mathrm{I}^2 \times \mathrm{R} \times 3 = 28.8^2 \times 0.332 \times 3 = 826.1\ \mathrm{W}$$

$$P_s(26.5) = P(26.5) - P_r(26.5_m) = 825.8 - 826.1 = -0.3\ \mathrm{W}$$

Form the calculation above, the stray losses is negative value. A more accurate method for measuring the stray losses was carried out by *Professor Guy Olivier*. A great quantity experiments indicate that the stray losses of the dry-type transformer are very small and it can be neglected as a small rated power units.

The load losses corrected at 30 °C are shown in table 2.5

Load current [A]		Aluminum transformer			
		$R_{eq}(\Omega)$	P [W]	T_m(°C)	P(30°C) [W]
$50\%I_n$	14.5	0.206	129.9	23.5	133.3
$60\%I_n$	17.3	0.212	190	24.5	194.2
$70\%I_n$	20.2	0.221	270.9	25.0	276.3
$80\%I_n$	23.2	0.225	363.2	25.5	369.7
$90\%I_n$	26.1	0.232	473.8	25.8	481.7
$100\%I_n$	28.85	0.240	600.3	27.0	607.4

A) Aluminum transformer

Load current[A]		Copper transformer			
		$R_{eq}(\Omega)$	P [W]	T(°C)	P(30°C) [W]
50%In	14.4	0.282	175.3	24.5	179.0
60%In	17.3	0.292	262.5	24.5	268.1
70%In	20.2	0.297	364	24	372.4
80%In	23.2	0.311	502	26	509.7
90%In	26.1	0.318	650.5	25.5	661.8
100%In	28.8	0.332	825.8	26.5	836.9

B) Copper transformer

Table2.5: Temperature correction of load losses

2.6.3 Calculation of test efficiency for dry-type transformer.[11]

According to the CSA-C802.2-06 "Minimum efficiency values for Dry-Type Transformers" [11], the transformer efficiency can be calculated by the equation as follows:

$$\%efficiency = \frac{100 \times P \times 1000}{P \times 1000 + NL + P_{75} \times P^2}$$

$$P_{75} = P_r \times T_{75} + \frac{P_s}{T_{75}}$$

$$T_{75} = \frac{T_k + 75}{T_k + T_{DC}}$$

$$\mathrm{P_{nc}} = \mathrm{P_{co}} \times \left(1 + 0.00065 \times \left(\mathrm{T_{nm}} - T_{nr}\right)\right)$$

Where

P:	Per unit load in accordance with technique data is 35% of full load.
kVA:	Nameplate kVA rating .
NL:	No-load loss in watts at 100% of the rated voltage and ambient temperature.
P_{75}:	Load losses in watts at 75°C.
P_r:	I^2R losses.
P_s:	Stray losses and eddy current losses.
P_{co}:	The no-load losses corrected for waveform distortion.
P_{nc}:	The no-load losses corrected for waveform distortion and then to the reference temperature of 20°C.
P_{nc}:	The no-load losses, corrected for waveform distortion at temperature T_{nm}.
T_{nm}:	The core temperature during the measurement of no-load losses.
T_{nr}:	Reference temperature 20°C
Tk :	234.5 $^{\circ}C$ for copper, 225 $^{\circ}C$ for aluminum.

The two transformers under test have a 30kVA rating and the calculations are as follows:

Copper Transformer:

$$P_{sc} = 825.8W$$
$$P_{co} = 203.9W$$
$$P_r = 825.8W$$
$$P_{r_{75}} = P_r * (234.5 + 75) / (234.5 + 26.5) = 979.3W$$
$$P_{nc} = P_{co} * (1 + 0.00065 * (68.5 - 20)) = 210.3W$$
$$\%efficiency = 0.35 * 30000 / (0.35 * 30000 + P_{nc} + P_{75} * 0.35^2) * 100 = 96.95$$

Aluminum transformer:

$$P_{sc} = 600.3W$$
$$P_{co} = 221.9W$$
$$P_r = 600.3W$$
$$P_{r_{75}} = P_r \times (225 + 75) / (225 + 27) = 714.6W$$
$$P_{nc} = P_{co} \times (1 + 0.00065 * (68 - 20)) = 228.4W$$
$$\%efficiency = 0.35 * 30000 / (0.35 * 30000 + Pnc + P75 * 0.35^2) * 100 = 97.08$$

2.6.4 Determination of the hot winding resistance

The hot resistances should be extrapolated back to the instant of shutdown of power supply by using a curve fitting technique. The following example based on the primary winding resistance of the copper transformer at full load will enable a better comprehension of the hot resistance determination.

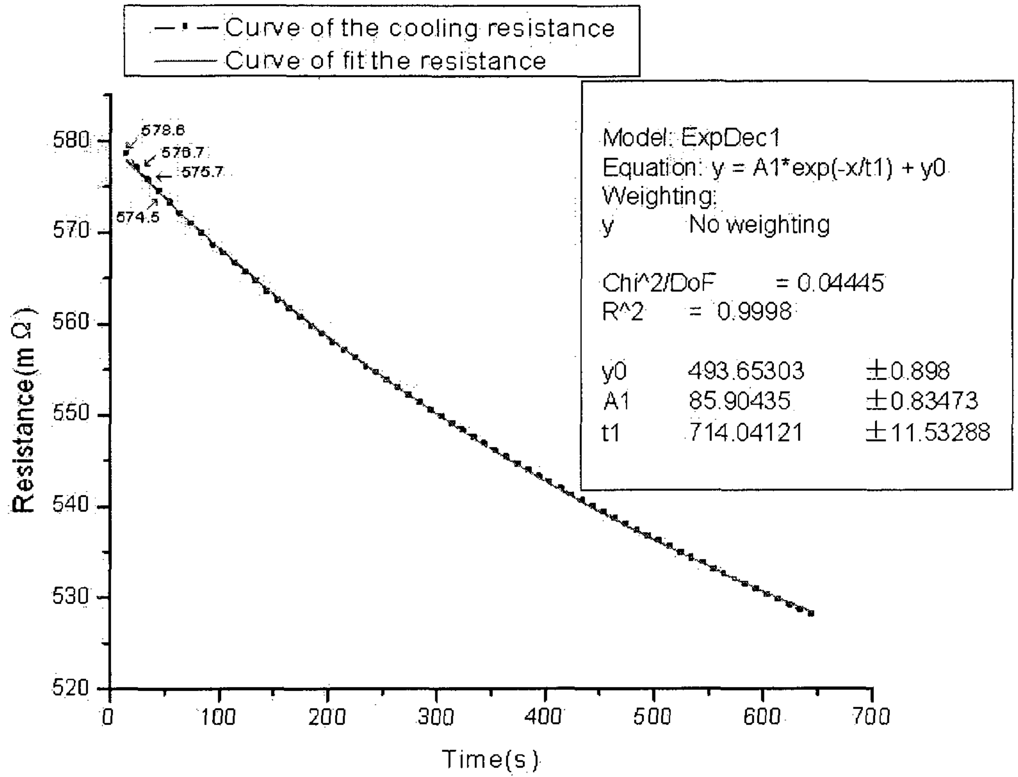


Figure2.14: Curve of the winding resistance cooling

In the figure 2.14, there is a delay between the first resistance measurement (578.6mΩ) and the instant of shut down, time '0'. This delay corresponds to the removal of the short-circuits cables and the connection of the dc power supplies to the current injection board and to the data acquisition system.

Using the fitting method, the equation of the cooling curve can be established. The fitting equation is: $y = A_1 * \exp(-x/t_1) + y_0$

where:

$$y_0 = 493.6$$

A_1=85.9

t_1=714.0

At time '0', we have y = A_1*exp (-0/t1) + y_0, and

$$y = 579.56(m\Omega) \text{ at } 26.5^\circ C.$$

Finally, corrected at 30℃:

$$R' = R \times \frac{(T_k + T_1)}{(T_k + T_2)} = 579.56 \times \frac{234.5 + 30}{234.5 + 26.5} = 587.3 \ m\Omega$$

With this method, all the resistances should be extrapolated back at '0' second. The hot resistances have to be corrected to the referred temperature, 30°C with the equation 1.2. The values are shown in the table 2.6.

Windings	Hot resistance measurement corrected at 30°C					
Aluminum	50% I_n	60% I_n	70% I_n	80% I_n	90% I_n	100% I_n
	m Ω	m Ω	m Ω	m Ω	m Ω	m Ω
Primary						
R_{p1}	299.2	307.8	316.9	327.0	337.9	349.6
R_{p2}	299.2	307.8	316.9	327.0	337.8	349.6
R_{p3}	297.6	306.4	315.3	324.4	334.9	346.1
Secondary						
R_{s1}	9.3	9.6	9.9	10.2	10.5	10.9
R_{s2}	9.3	9.6	9.9	10.2	10.5	11.0
R_{s3}	9.3	9.6	9.9	10.2	10.6	11.0

A) Aluminum transformer

Windings	Hot resistance measurement corrected at 30°C					
Copper	50% I_n	60% I_n	70% I_n	80% I_n	90% I_n	100% I_n
	m Ω	m Ω	m Ω	m Ω	m Ω	m Ω
Primary						
R_{p1}	487.5	504.7	520.6	539.2	563.7	587.3
R_{p2}	487.5	504.6	520.6	539.2	563.7	587.3
R_{p3}	480.8	495.6	509.9	527.2	548.8	570.3
Secondary						
R_{s1}	11.0	11.3	11.7	12.1	12.5	13.1
R_{s2}	11.1	11.4	11.8	12.1	12.6	13.2
R_{s3}	11.0	11.2	11.5	11.9	12.3	12.8

B) Copper transformer

Table 2.6: Hot resistance measurement corrected at 30°C from the short circuit test

2.6.5 Calculation of the temperature rise from the short circuit test

With the cold resistance and the hot resistances measured above, the temperature rise can be calculated from the equations 1.3 to 1.5. The values of temperature rise corrected at 30 °C are shown in table 2.7.

Windings	Temperature rise corrected at 30°C					
Aluminum	50% I_n	60% I_n	70% I_n	80% I_n	90% I_n	100% I_n
	°C	°C	°C	°C	°C	°C
Primary						
R_{p1}	17.2	26.2	35.0	44.8	55.1	63.0
R_{p2}	20.2	29.3	38.2	48.1	58.4	66.5
R_{p3}	17.8	26.9	35.6	44.6	54.6	62.1
Secondary						
R_{s1}	17.9	26.8	35.8	44.7	53.7	62.8
R_{s2}	21.1	30.2	39.2	48.4	58.8	69.5
R_{s3}	17.9	26.8	35.8	46.4	56.7	65.7

A) Aluminum transformer

Windings	Temperature rise corrected at 30°C					
Copper	50% S_{nom}	60% S_{nom}	70% S_{nom}	80% S_{nom}	90% S_{nom}	100%S_{nom}
	°C	°C	°C	°C	°C	°C
Primary						
R_{p1}	25.0	35.1	43.8	57.3	71.2	82.8
R_{p2}	27.0	37.1	46.0	59.5	73.5	85.2
R_{p3}	25.0	33.8	41.7	54.6	66.9	77.3
Secondary						
R_{s1}	21.9	29.8	38.5	50.9	61.4	73.4
R_{s2}	24.5	32.4	40.3	52.3	64.1	76.0
R_{s3}	19.6	26.3	34.7	44.7	55.2	65.7

B) Copper transformer

Table2.7: The temperature rise form the short circuit test corrected at 30°C

Since there is a different temperature rise among the windings due to the inner ventilation of the transformer, the average temperature rise of the transformer is determined and the results are shown in table 2.8.

Load current [A]	Aluminum transformer		Copper transformer	
	Primary windings[°C]	Secondary windings [°C]	Primary windings [°C]	Secondary windings [°C]
50%I_n	18.4	19.0	25.7	22
60%I_n	27.5	27.9	35.3	29.5
70%I_n	36.3	36.9	43.8	37.7
80%I_n	45.8	46.5	57.1	49.3
90%I_n	56.0	56.4	70.5	60.2
100%I_n	63.9	66.0	81.8	71.7

Table 2.8: The average temperature rise of primary and secondary from short circuit test

The graphs of the average temperature rise of the aluminum and the copper transformers are shown in figure 2.15 and figure 2.16.

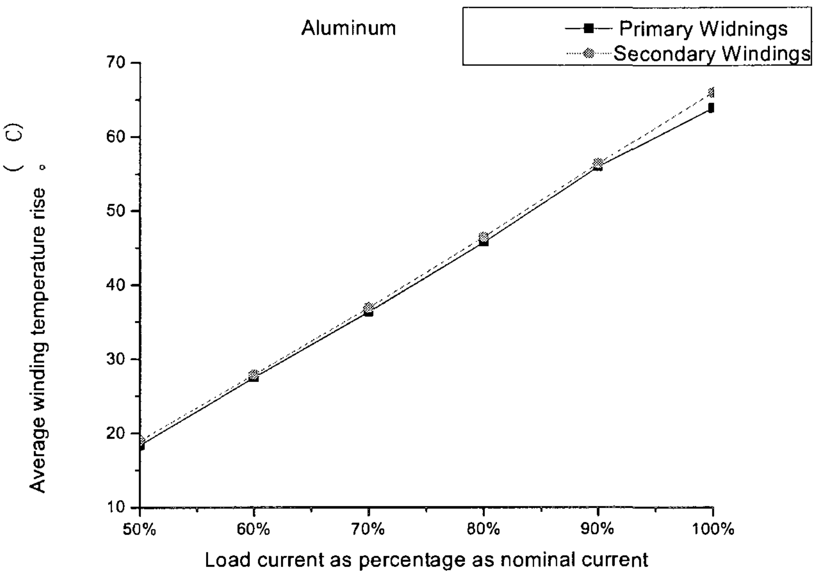


Figure2.15 Average temperature rise for the aluminum transformer

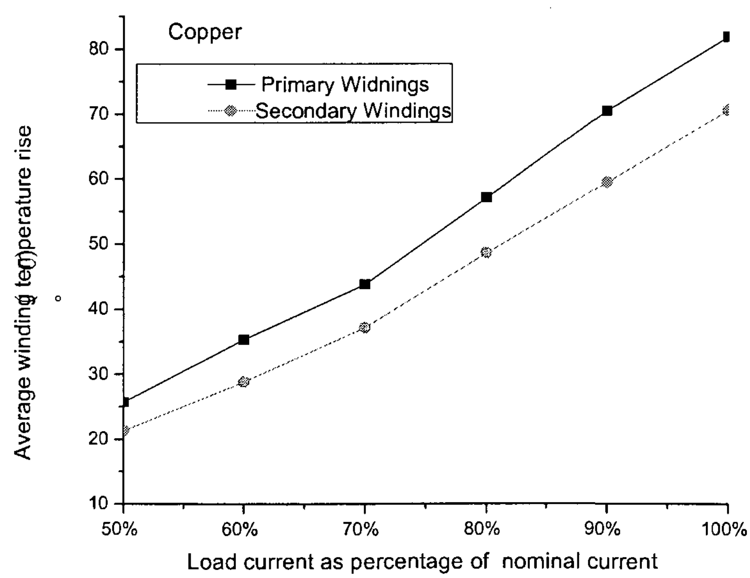


Figure2.16: Average temperature rise for the copper transformer

The temperature rise of the hot spot should be considered. Normally, the hot spot is taken to be 40 degrees higher than the average temperature rise.

Hence the hot spot temperature is become critical for the reliability of the transformer; it should be taken under the hot spot value. The temperature measured by the thermocouple (figure 2.17) installed near the expected location of the hot spot is shown in table 2.9 and in figure 2.18.

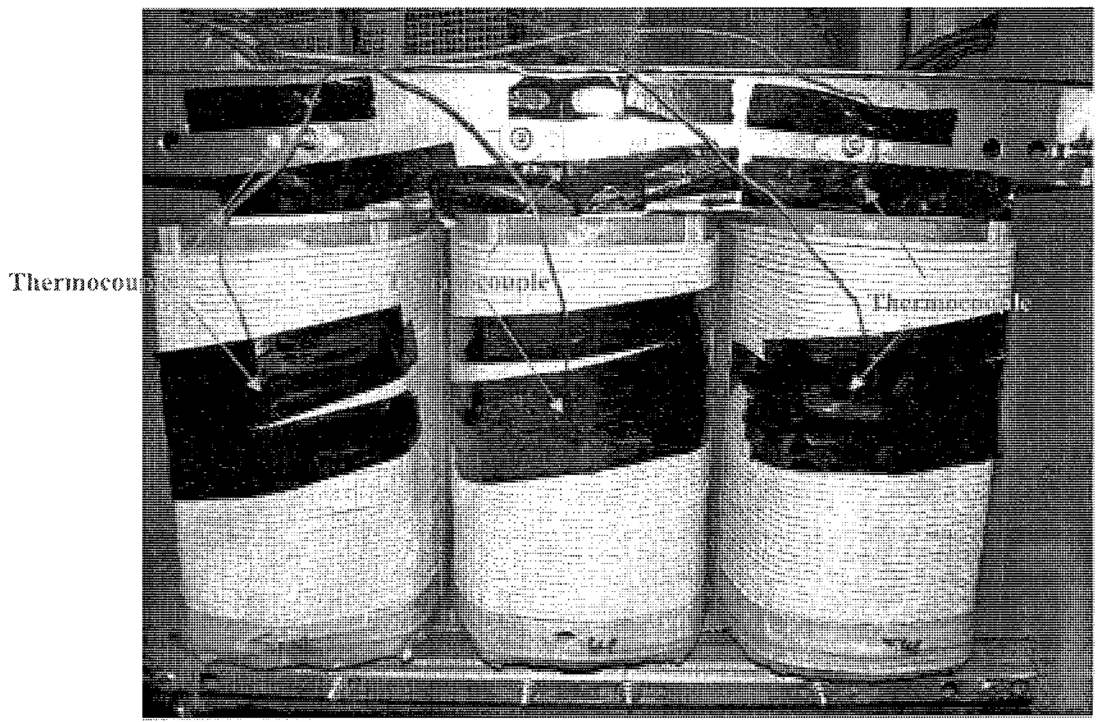
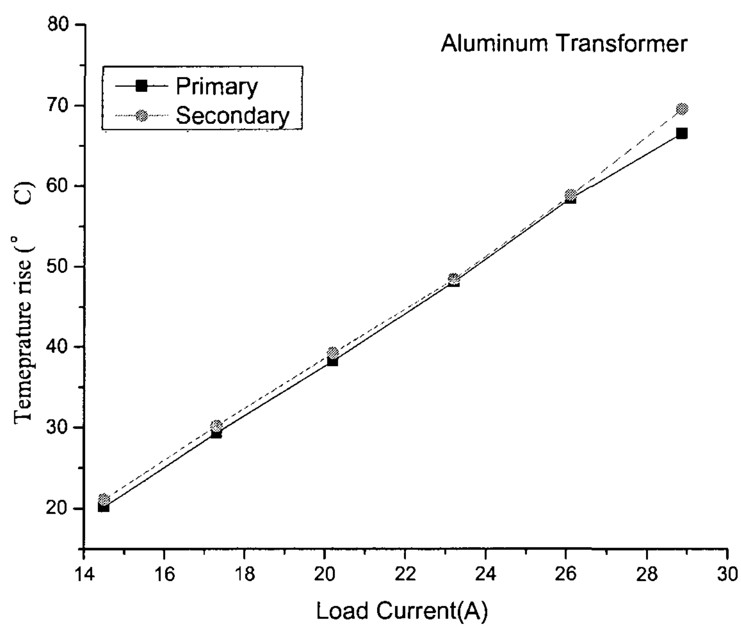


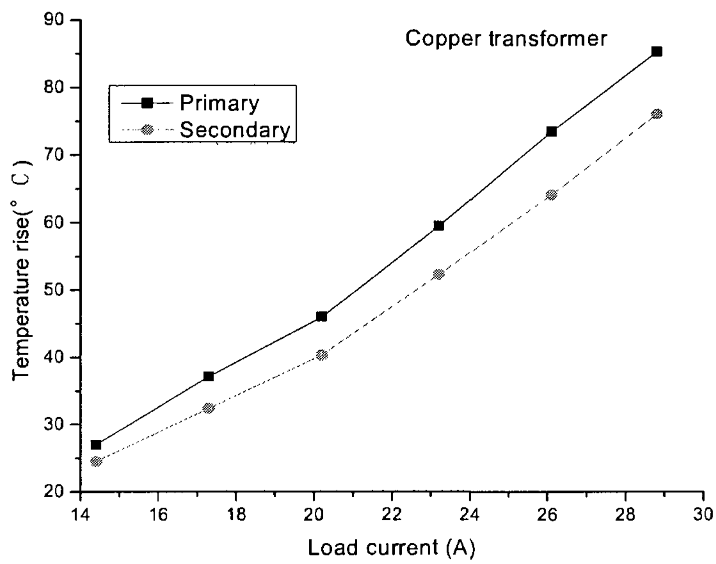
Figure2.17: Locations of the thermocouples

Load current [A]	Aluminum transformer		Copper transformer	
	Primary windings[°C]	Secondary windings[°C]	Primary windings[°C]	Secondary windings[°C]
50%I_n	20.2	21.1	27	24.5
60%I_n	29.3	30.2	37.1	32.4
70%I_n	38.2	39.2	46	40.3
80%I_n	48.1	48.4	59.5	52.3
90%I_n	58.4	58.8	73.5	64.1
100%I_n	66.5	69.5	85.2	76

Table 2.9: The highest temperature rise at location near the expected hot spot during short-circuit test



A) Aluminum Transformer



B) Copper transformer

Figure2.18: The maximum temperature rise measured during the short circuit test

Conclusion

In this section the equivalent circuit under short circuit test has been studied. With the equivalent parameters, the load losses correction for the temperature and the test efficiency of the two transformers have been calculated according to the standards.

Secondly, the temperature rise from the specified load current has been studied and the results of the average temperature rise and the temperature rise on the hot spot obtained from the short circuit test have been calculated.

2.7 CALCULATION OF THE TOTAL WINDING TEMPERATURE RISE

The total winding temperature rise can be calculated from the open circuit test and short circuit test by the following equation given in ANSI/IEEE C57.12.91-2001 [1]:

$$T_t = T_c[1+\left(\frac{T_e}{T_c}\right)^{1.25}]^{0.8}$$

T_c is the temperature rise from the short-circuit test and T_e is the temperature rise due to the excitation losses. T_t is the total temperature rise of each unit. The total winding temperature rise corrected at 30 °C is shown in table 2.10.

Aluminum	T_e	50% I_n		60% I_n		70% I_n		80% I_n		90% I_n		100% I_n	
Temperature rise corrected at 30 °C	(°C)	T_c (°C)	T_t (°C)	T_c (°C)	T_t (°C)	T_c (°C)	T_t (°C)	T_c (°C)	T_t (°C)	T_c (°C)	T_t (°C)	T_c (°C)	T_t (°C)
Primary													
R_{p1}	16.2	17.2	29.1	26.2	37.2	35.0	45.3	44.8	54.6	55.1	64.4	63.0	72.0
R_{p2}	18	20.2	33.3	29.3	41.5	38.2	49.7	48.1	59.1	58.4	68.9	66.5	76.7
R_{p3}	17.5	17.8	30.7	26.9	38.9	35.6	46.9	44.6	55.4	54.6	64.9	62.1	72.1
Secondary													
R_{s1}	29.2	17.9	41.3	26.8	48.8	35.8	56.6	44.7	64.7	53.7	72.9	62.8	81.4
R_{s2}	32.2	21.1	46.7	30.2	54.3	39.2	62.3	48.4	70.5	58.8	80.1	69.5	90.0
R_{s3}	27.5	17.9	39.7	26.8	47.3	35.8	55.2	46.4	64.8	56.7	74.4	65.7	82.9

A) The total temperature rise of aluminum transformer

Copper	T_e	50% I_n		60% I_n		70% I_n		80% I_n		90% I_n		100% I_n	
Temperature rise corrected at 30 °C	(°C)	T_c (°C)	T_t (°C)	T_c (°C)	T_t (°C)	T_c (°C)	T_t (°C)	T_c (°C)	T_t (°C)	T_c (°C)	T_t (°C)	T_c (°C)	T_t (°C)
Primary													
R_{p1}	12.7	25.0	33.2	35.1	42.8	43.8	51.2	57.3	64.2	71.2	77.7	82.8	89.1
R_{p2}	14.6	27.0	36.6	37.1	46.1	46.0	54.5	59.5	67.6	73.5	81.2	85.2	92.6
R_{p3}	13.7	25.0	34.0	33.8	42.3	41.7	49.8	54.6	62.2	66.9	74.2	77.3	84.3
Secondary													
R_{s1}	21.9	21.9	38.1	29.8	45.1	38.5	53.1	50.9	64.7	61.4	74.6	73.4	86.1
R_{s2}	24.5	24.5	42.7	32.4	49.7	40.3	56.8	52.3	67.9	64.1	79.1	76.0	90.5
R_{s3}	24.3	19.6	38.3	26.3	44.1	32.7	49.7	44.7	60.8	55.2	70.6	65.7	80.4

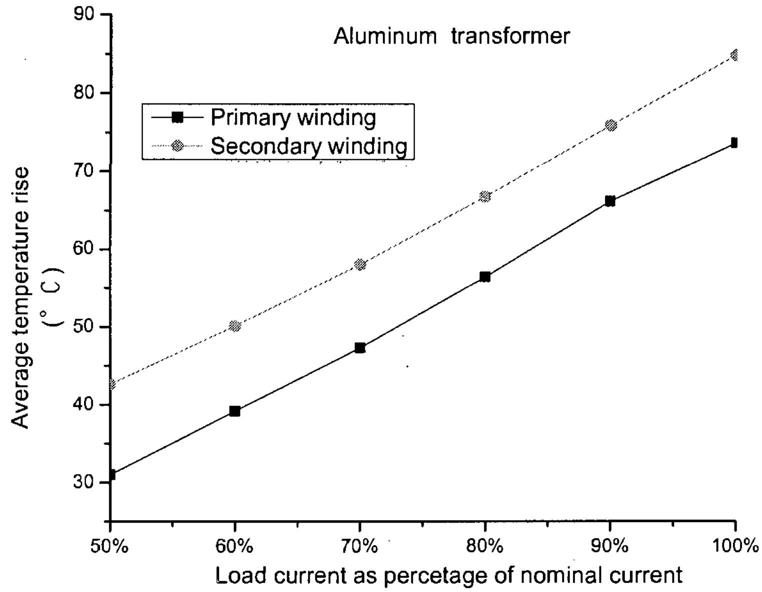
B) The total temperature rise of copper transformer

Table 2.10: The total temperature rise of each winding corrected at 30°C

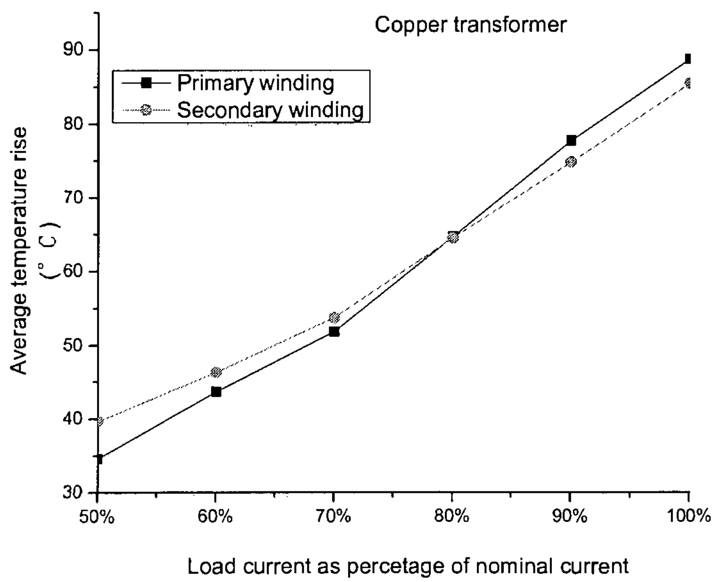
In order to reduce the influence of the winding location, the average temperature rise should be considered. The results are shown in table 2.11 and in figure 2.19

Load current [A]	Aluminum transformer		Copper transformer	
	Primary windings[°C]	Secondary windings[°C]	Primary windings[°C]	Secondary windings[°C]
$50\%I_n=14.5$	31.0	42.6	34.6	39.7
$60\%I_n=17.3$	39.2	50.1	43.7	46.3
$70\%I_n=20.2$	47.3	58.0	51.8	53.7
$80\%I_n=23.1$	56.4	66.7	64.7	64.5
$90\%I_n=26.0$	66.1	75.8	77.7	74.8
$I_n=28.9A$	73.6	84.8	88.7	85.4

Table 2.11: The average temperature rise of primary and secondary windings



A) Aluminum transformer



B) Copper transformer

Figure2.19: The average temperature rise of the transformers

The ANSI Standard C57.96-1999 and the CSA Standard C9.1-M1981 entitled "Guide for Loading Dry-Type Distribution and Power Transformers" proposes the following empirical formula to predict the temperature rise of a transformer:

For a self-cooling transformer

$$\Delta T = K \times S^{2m}$$

Where,

ΔT = average temperature rise

K= constant

S= apparent power of the load

m= is an empirical constant, which is equal to 0.8

With this empirical rule, the total temperature rises of the two transformers which we measured can be verified. The figure 2.20 gives the average temperature rise versus total losses for the two transformers. These losses include core losses and winding losses and the table 2.12 shows the total losses of the two transformers.

Aluminum transformer		Copper transformer	
Temperature Rise [°C]	Total transformer losses [W]	Temperature Rise[°C]	Total transformer losses [W]
36.8	351.4	37.2	379.2
44.7	411.5	45	466.4
52.7	492.4	53.8	567.9
61.6	584.7	64.6	705.9
71	695.3	76.3	854.4
79.2	821.8	87.1	1029.7

Table 2.12: The transformer total losses

And the following relations between temperature rise ΔT and the total losses were obtained using standard numerical curve fitting techniques.

$$\Delta T_{AL}=0.1991\times P^{2\times 0.89663}$$

$$\Delta T_{CP}=0.2326\times P^{2\times 0.85665}$$

Where

ΔT_{AL} = Average temperature rise of the aluminum transformer;

ΔT_{CP} = Average temperature rise of the copper transformer.

P = The total transformer losses including core losses and winding losses.

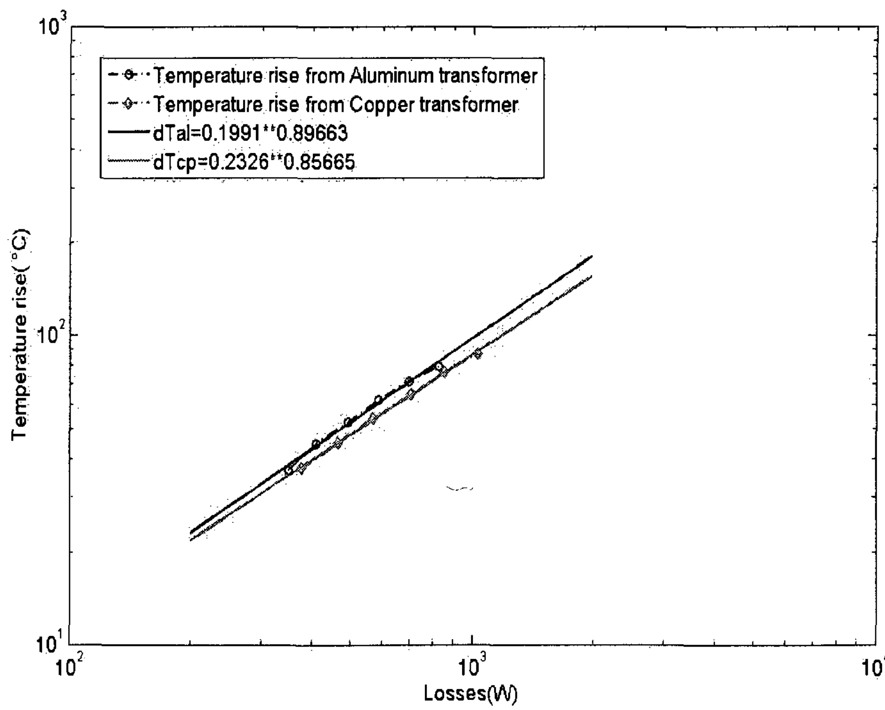


Figure 2.20: Temperature rise versus losses

The standards suggest 0.8 as the empirical value for the exponent associated with the losses. The measured values are closer to 0.9

Conclusion

In this section, the calculation of the total temperature rise from the excitation loss and the rated current has been studied. The total temperature rise has been determined using the temperature rise from the open circuit test and short circuit test. The results of the temperature rise of the two transformers have been verified.

CHAPITRE 3

THE TOTAL TEMPERATURE RISE OBTAINED FROM LOADING BACK METHOD

Introduction

The loading back method is a basic method to test dry-type transformers that can be used when more than one transformer is available. It is often called opposition method or back to back method. The total winding temperature rise can be determined by this method.

3.1 ANALYSIS OF THE LOADING BACK METHOD

The basic connection of two single-phase transformers under loading back method is shown in Figure 3.1.

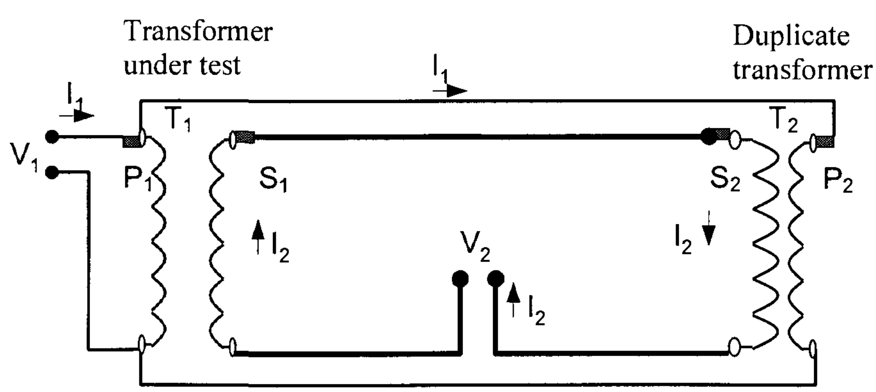


Figure 3.1: Connection of single-phase transformers under loading back test

Where

T_1: The transformer under test;

T_2: The duplicated transformer of T_1;

V_1: The variable source 1;

V_2: The variable source 2;

I_1: The current in the primary winding;

I_2: The current in the secondary winding;

In figure 3.1, T_1 and T_2 have the same voltage and power. The primary windings (P1, P2) of the two transformers, T_1 and T_2, are in parallel connection and the secondary windings (S1, S2) are in series connection. V_1 provides the nominal voltage at rated frequency, the total excitation current and excitation losses of T_1 and T_2.

On the other side, V_2 provides the specified load current of the secondary and the impedance losses of the two transformers. In the loading back method, the current I_2 in the secondary windings can be expressed as:

$$I_2 = \frac{U_{s2}}{Z_1 + Z_2}$$

Where

U_{s2}: The voltage of the variable source V_2

Z_1: The equivalent impedance of T_1

Z_2: The equivalent impedance of T_2

When the load current I_2 is equal to the nominal current I_n, the two transformers are at rated load.

According to the standard ANSI/IEEE C57.12.91-2001 [1], the circulating current though the winding should be fixed as follows:

- This current should be at rated frequency ($\pm$ 10%).
- The correction are applied when the circulating current is not the rated value

This is not an absolute requirement even if this test has two identical units. The second transformer can be different as long as its power rating and voltages are adequate.

3.2 THE TOTAL TEMPERATURE RISE MEASURED FORM LOADING BACK METHOD ANSI/IEEE C57.12.91-2001 [1]

Figure 3.2 shows the schematic of the three-phase transformers under the loading back method. The primary windings of two transformers are connected in delta and supplied by the variable transformer 1. The secondary windings are in wye and supplied, in the laboratory by three 36kVA single-phase Marcus transformers which rated voltages are 360V/36V. The Marcus transformers are used to supply the circulating load current in the secondary windings of the transformers under test. The Marcus transformers are connected to the variable transformer 2.

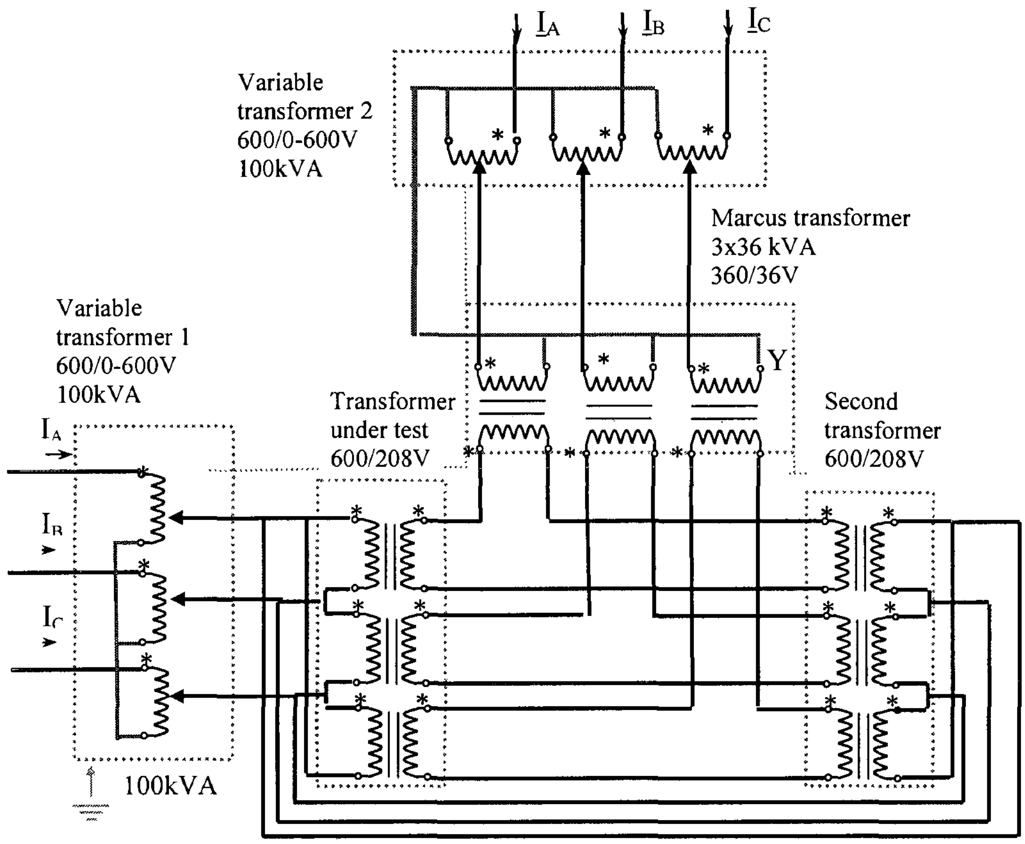


Figure 3.2: Connection of three-phase transformer under loading back test

The power analyzer, Voltech PM-6000, is simultaneously connected to the primary and secondary windings to measure the voltages, currents and the power losses. The six current transformers are used to reduce the current to an acceptable value for the analyzer which is limited to a maximum 30 A. The data acquisition system is used to record the winding temperature readings from thermocouples. The schematic of the loading back test in the laboratory is in shown in figure 3.3.

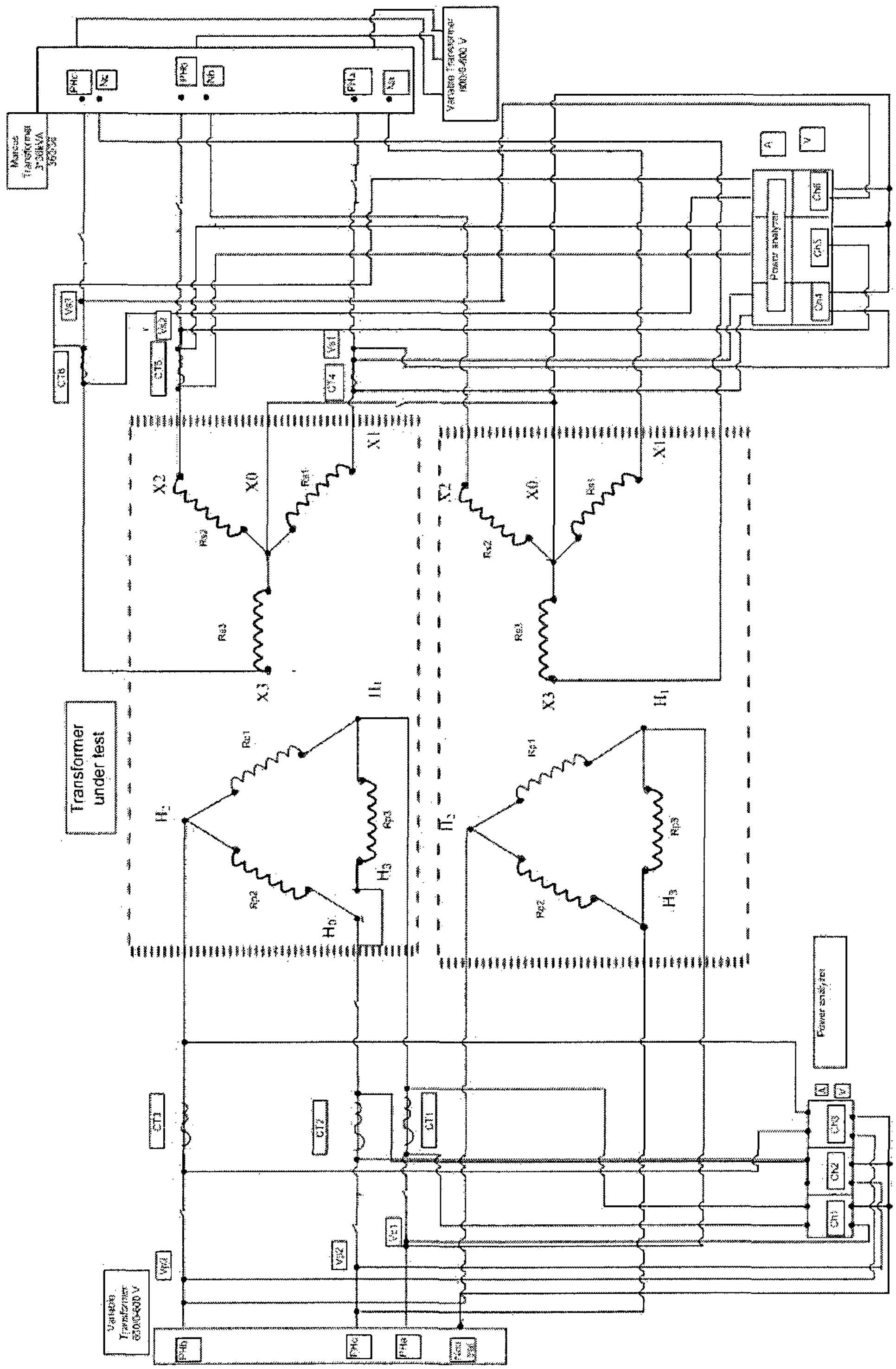


Figure 3.3: Schematic of back to back test installation in the laboratory

When the winding temperature is stabilized, the breakers are opened. Then dc currents are immediately injected into the winding. The values of winding resistances are recorded by the data acquisition system each 10 seconds. The hot resistance measurement procedure is the same process as described for the short circuit test. The total winding temperature can be calculated as described in 1.2.

3.3 EXPERIMENTAL RESULTS FOR LOADING BACK METHOD

The temperature rise of both transformers, the aluminum and copper 30 kVA units, were determined by the loading back method.

3.3.1 Hot winding resistance measurement

Table 3.1 gives the measured values of the winding resistances corrected to 30°C. The procedure is identical as described for the short-circuit test previously.

Windings	Hot resistance measurement corrected to 30°C					
Aluminum	50% I_n	60% I_n	70% I_n	80% I_n	90% I_n	100% I_n
	mΩ	mΩ	mΩ	mΩ	mΩ	mΩ
Primary						
R_{p1}	314.3	321.0	328.7	337.6	348.2	359.7
R_{p2}	314.3	321.0	328.7	337.6	348.2	359.7
R_{p3}	311.7	319.2	326.1	335.2	345.3	355.7
Secondary						
R_{s1}	10.0	10.3	10.4	10.9	11.1	11.5
R_{s2}	10.0	10.4	10.5	11.0	11.3	11.7
R_{s3}	10.0	10.3	10.4	10.9	11.1	11.5

A) Aluminum transformer

Windings	Hot resistance measurement corrected to 30°C					
Copper	50% I_n	60% I_n	70% I_n	80% I_n	90% I_n	100% I_n
	mΩ	mΩ	mΩ	mΩ	mΩ	mΩ
Primary						
R_{p1}	499.5	515.3	534.1	550.5	572.9	600.7
R_{p2}	499.5	515.3	534.2	550.9	572.9	600.7
R_{p3}	491.6	504.4	521.9	537.1	556.8	580.6
Secondary						
R_{s1}	11.6	11.9	12.3	12.7	13.0	13.6
R_{s2}	11.7	12.1	12.4	12.8	13.2	13.8
R_{s3}	11.6	11.9	12.1	12.4	12.9	13.3

B) Copper transformer

Table 3.1: Hot resistance measured from the loading back method

3.3.2 Calculation of the temperature rise from loading back test

With the hot and cold resistances values, the temperature rise can easily be estimated using equations 1.3 and 1.5. The corrected values to a reference temperature, 30 °C, are given in table 3.2.

Windings	Temperature rise corrected to 30°C					
Aluminum	50% I_n	60% I_n	70% I_n	80% I_n	90% I_n	100% I_n
	°C	°C	°C	°C	°C	°C
Primary						
R_{p1}	34.4	40.0	46.9	53.8	63.4	71.8
R_{p2}	37.6	43.2	50.3	57.2	66.9	75.5
R_{p3}	34.1	40.5	46.8	53.8	63.1	70.7
Secondary						
R_{s1}	42.5	48.5	56.5	64.5	72.8	82.1
R_{s2}	43.9	52.9	58.9	69.1	78.3	88.6
R_{s3}	42.2	49.3	55.3	64.1	72.7	81.7

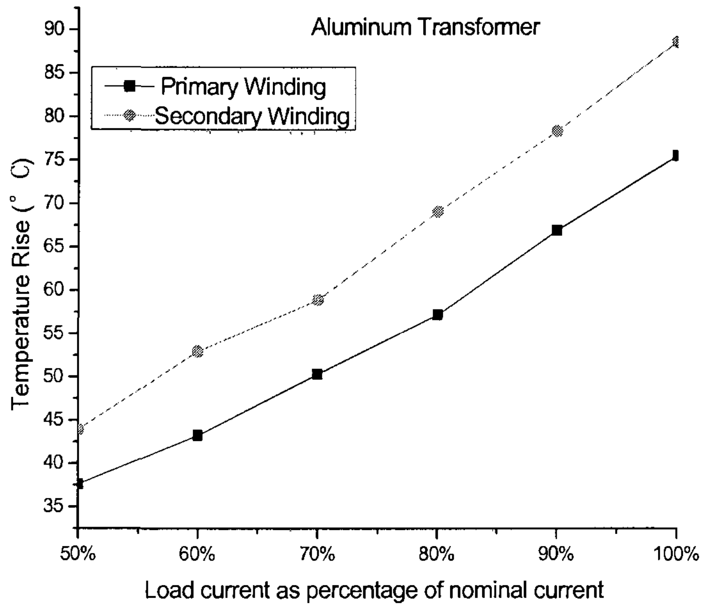
A) Aluminum transformer

Windings	Temperature rise corrected to 30°C					
Copper	50% I_n	60% I_n	70% I_n	80% I_n	90% I_n	100% I_n
	°C	°C	°C	°C	°C	°C
Primary						
R_{p1}	32.0	43.2	53.7	64.7	77.3	90.4
R_{p2}	34.0	45.3	55.9	67.2	79.7	92.9
R_{p3}	31.4	40.9	50.8	61.2	72.4	83.3
Secondary						
R_{s1}	37.7	47.0	55.9	66.8	76.0	87.1
R_{s2}	40.3	50.9	58.8	70.2	80.4	91.6
R_{s3}	35.2	45.5	50.0	59.0	71.0	78.2

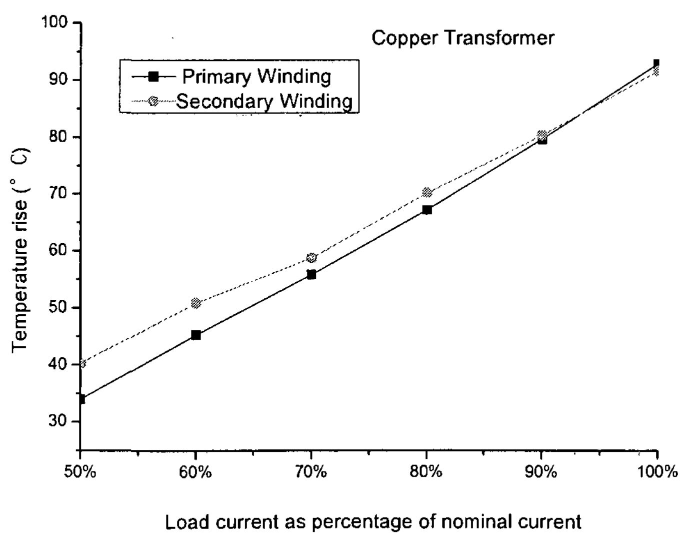
B) Copper transformer

Table 3.2: Temperature rise of each winding from the loading back method

The temperature rise of the center leg windings is significantly higher than the rise of the other two phases located on the exterior legs. The temperature rise of the highest temperature measured by the thermocouples is given in figure 3.3. Since the real hot spot position was not determined experimentally, the actual hot spot temperature might be considerably different.



A) Aluminum transformer



B) Copper transformer

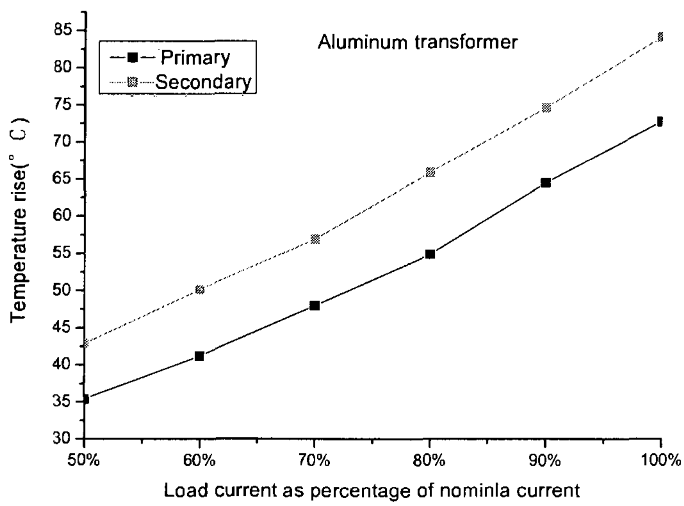
Figure 3.4: The maximum temperature rise obtained during the loading back tests

To reduce the effects due to the ventilation of the transformers, the average temperature rise of windings of each phase are calculated and the values are shown in table 3.3.

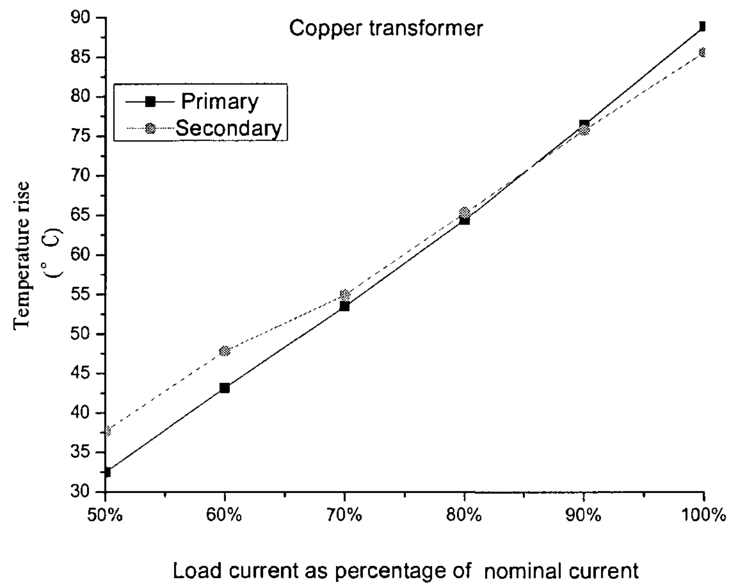
Load current [A]	Aluminum transformer		Copper transformer	
	Primary temperature[°C]	Secondary temperature[°C]	Primary temperature[°C]	Secondary temperature[°C]
$50\%I_n$=14.5	35.4	42.9	32.5	37.7
$60\%I_n$=17.3	41.2	50.2	43.1	47.8
$70\%I_n$=20.2	48	56.9	53.5	54.9
$80\%I_n$=23.1	54.9	65.9	64.4	65.3
$90\%I_n$=26.0	64.5	74.6	76.5	75.8
I_n=28.9A	72.7	84.1	88.9	85.6

Table 3.3: Average temperature rise from the loading back method

The graphs of the average winding temperature rise are shown in figure 3.4



A) Aluminum Transformer



B) Copper transformer

Figure 3.5: The average temperature rise from the loading back method

Conclusions

With the loading back method the total temperature rise of each unit can be determined directly. During this test, the duplicate transformer is also supplied by the electric power and produces a large quantity of heat which can affect the ambient temperature and the hot resistance should be considered.

Comparing with the separate excitation loss and rated current method, the loading back method requires more complex testing facilities and auxiliary equipments which results in much larger energy consumption.

CHAPITRE 4

COMPARISON OF TEMPERATURE RISE FROM TWO EXPERIMENTAL METHODS

Introduction

In this chapter, the temperature rise measurement results obtained from the two methods, the separate excitation loss and rated current method and the loading back method are analyzed and compared.

4.1 THE TOTAL TEMPERATURE RISE OBTAINED FROM THE SEPARATE EXCITATION LOSS AND RATED CURRENT METHOD

The total temperature rise of the two transformers, the aluminum and copper transformer are compared by using the separate excitation loss and rated current method.

The analysis is limited to the average temperature rise for the reason of reducing the temperature variations due to ventilation differences. The values of average winding temperature rise have been evaluated in Chapter 2 and the results are shown in table 4.1.

Load current[A]	Temperature rise	
	Aluminum transformer[°C]	Copper transformer [°C]
$50\%I_n=14.5$	36.8	37.2
$60\%I_n=17.3$	44.7	45.0
$70\%I_n=20.2$	52.7	53.8
$80\%I_n=23.1$	61.6	64.6
$90\%I_n=26.0$	71.0	76.3
$I_n=28.9$	79.2	87.1

Table4.1: Average temperature rise from the excitation loss and rated current method

The figure 4.1 presents the average temperature rise of the two transformers; copper and aluminum transformer obtained from the separate excitation loss and rated current method at each load current.

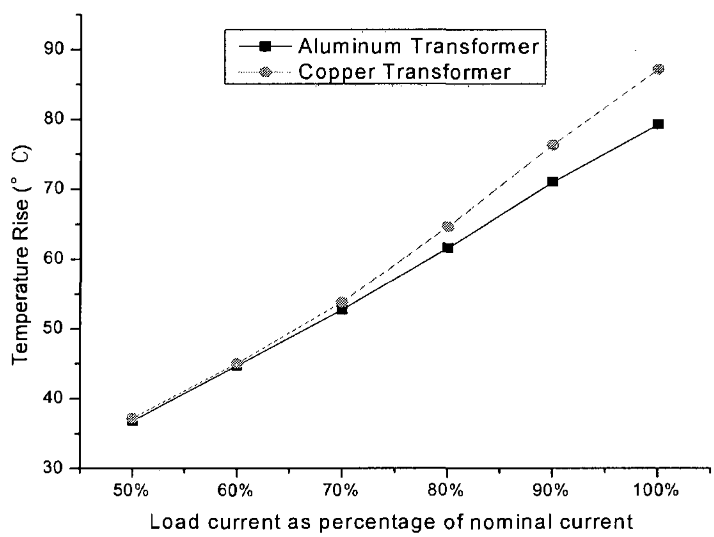


Figure 4.1: The average temperature rise from the excitation loss and rated current method

4.2 THE TOTAL TEMPERATURE RISE OBTAINED FROM THE LOADING BACK METHOD

The values of the total temperature rise from the loading back method were obtained in chapter 3. The average temperature rise of each unit from this method is given in table 4.2.

Load Current [A]	Temperature Rise	
	Aluminum Transformer [°C]	Copper Transformer[°C]
50%I_n=14.5	39.1	35.1
60%I_n=17.3	45.7	45.5
70%I_n=20.2	52.5	54.2
80%I_n=23.1	60.4	64.9
90%I_n=26.0	69.5	76.1
I_n=28.9	78.4	87.3

Table: 4.2: The average temperature rise from the loading back method

In the figure 4.2, it presents the average temperature rise from the loading back method of the two transformers at each load current.

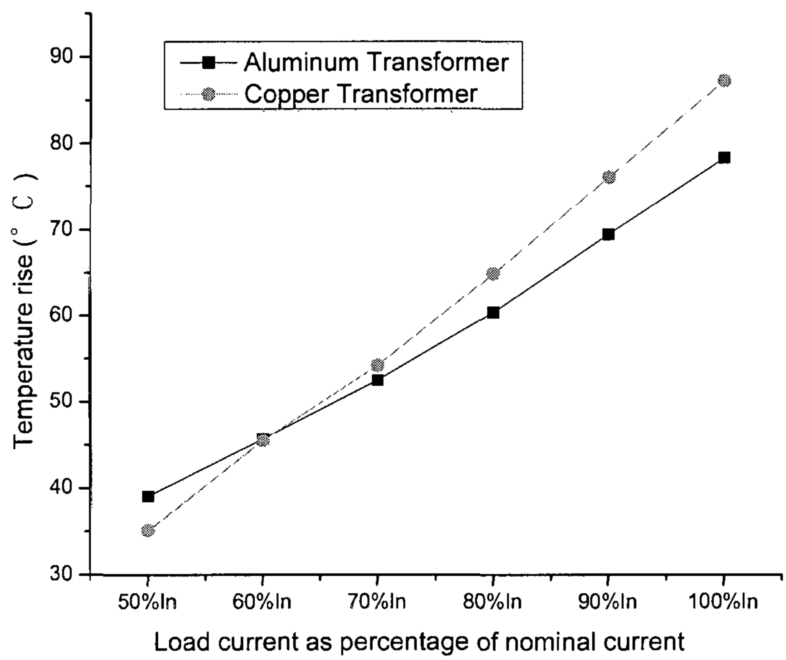


Figure 4.2: The average temperature rise from the loading back method

4.3 COMPARISON OF THE TOTAL TEMPERATURE RISE FROM THE TWO METHODS

One of the most important purposes of our research is to verify the reliability of the total temperature rise calculated by the excitation loss and rated current method. In this section, the total temperature rise determined by the excitation loss and rated current method and the loading back method are compared to verify the reliability of the tests.

The total temperature rise of the aluminum transformer obtained from the two methods is shown in table 4.3.

Load Current [A]	The total temperature rise of the Aluminum transformer	
	The separate excitation loss and rated current method[°C]	The loading back method [°C]
$50\%I_n=14.5$	36.8	39.1
$60\%I_n=17.3$	44.7	45.7
$70\%I_n=20.2$	52.7	52.5
$80\%I_n=23.1$	61.6	60.4
$90\%I_n=26.0$	71.0	69.5
$I_n=28.9$	79.2	78.4

Table: 4.3: The average total temperature rise of aluminum transformer

The figure 4.3 shows the comparison of the average total temperature rise of the aluminum transformer obtained from the two methods.

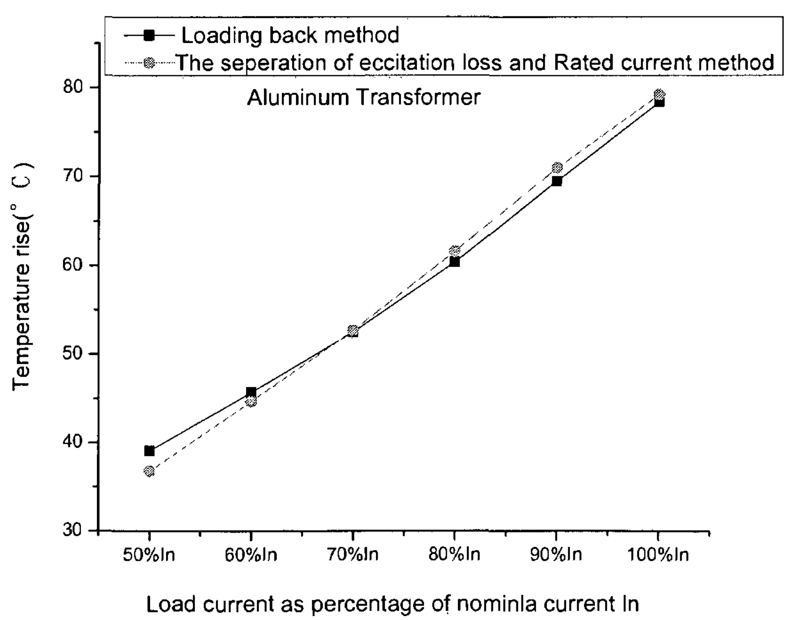


Figure 4.3: The temperature rise of aluminum transformer from the two methods

The total temperature rise of the copper transformer from the two methods is shown in table 4.4. The comparison of the average total temperature rise of the copper transformer obtained from the two methods is given in the figure 4.4.

Load Current [A]	The total temperature rise of the Copper transformer	
	The separate excitation loss and rated current method [°C]	The loading back method [°C]
$50\%I_n=14.5$	37.2	35.1
$60\%I_n=17.3$	45.0	45.5
$70\%I_n=20.2$	53.8	54.2
$80\%I_n=23.1$	64.6	64.9
$90\%I_n=26.0$	76.3	76.1
$I_n=28.9$	87.1	87.3

Table: 4.4: The average temperature rise of Copper transformer

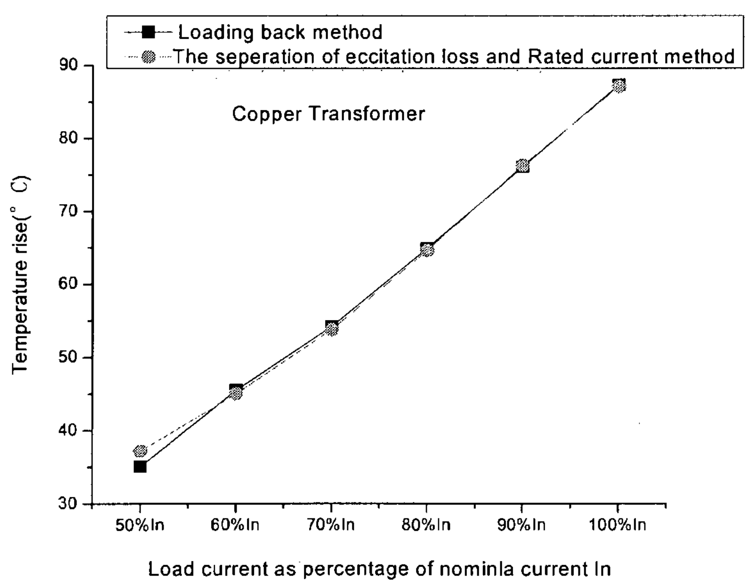


Figure 4.4: The average temperature rise of copper transformer from the two methods

Conclusion

In this chapter, the results from the two methods, the separate excitation loss and rated current method and the loading back method, determination of the temperature rise of transformers are compared and studied. As shown in figure 4.4 and 4.5, the results from the separate excitation loss and rated current method and the loading back method are equivalent. The equation $T_t = T_c[1+\left(\frac{T_e}{T_c}\right)^{1.25}]^{0.8}$ in IEEE standard C57.1.91-2001 is accurate to calculate the total temperature rise.

In the laboratory, both methods can be used to determine the thermal behavior of the dry type transformers. When considering the energy consumption and the test equipment, the separation excitation loss and the rated current method seems to be preferable.

CHAPITRE 5

CONCLUSIONS AND RECOMMADATIONS

5.1 CONCLUSIONS

Several methods can be used to determine the transformer temperature rise. In this project, we compared the measurement results of the temperature rise obtained from the separate excitation loss and rated current method and the loading back method

Hence the following conclusions can be drawn:

- The equation $T_t = T_c[1+\left(\frac{T_e}{T_c}\right)^{1.25}]^{0.8}$ from the standard ANSI / IEEE C57.12.91 - 2001, Standard Test Code for Dry Type Distribution and Power Transformers has been verified and found to be accurate.

- The temperature rise from the separated excitation loss and rated current method and the loading back method has been validated and both methods can be used to determine the temperature rise of the dry type transformer effectively.

- The test bench used in our lab has been validated and the experimental set up found to be adequate as prescribed by the standards.

- The test efficiency has been calculated according to the standard CSA-C802.2-06 Minimum efficiency values for Dry-Type Transformers.

5.2 RECOMMENDATIONS

Based on our findings for this research project, the following recommendations for further studies are made:

- Add an ac filter to reduce the harmonics in the laboratory 600V feeder.
- Explain the small temperature difference between the ambient temperature in the laboratory measured by thermometers and the cold winding temperature obtained from thermocouples.
- During the loading back test, the heat produced by the second transformer should be limited in order to obtain a more stable laboratory temperature.
- Try to implement a way to obtain the hot resistance value in real time to avoid the extrapolation of the winding temperature at the end of the test.
- Explain the differences between the dc resistance values obtained by the bridge method and the dc current source measurements method.
- Perform tests with non linear loads and compare the temperature rise obtained with linear loads of the same power rating.

REFERENCE

ANSI/IEEE Standards

[1] ANSI / IEEE C57.12.91 - 2001, *Standard Test Code For Dry Type Distribution And Power Transformers.*

[2] ANSI / IEEE C57.12.01 - 1998, *Standard General Requirements for Dry Type Distribution Power Transformers.*

[3] ANSI / IEEE C57.123-2002, *Guide for Transformer Loss Measurement*

[4] ANSI / IEEE C57.96-1999, *Guide for Loading Dry-Type Distribution and Power Transformers*

[5] NEMA Standard. 20, *Dry-Type Transformer for general applications.*

[6] NEMA Standards Publication TP 1-2002, *Guide for Determining Energy Efficiency for Distribution Transformers.*

[7] NEMA Standards Publication TP 2-2005, *Standard Test Method for Measuring the Energy consumption of Distribution Transformers.*

[8] Underwriters Laboratories UL 1561, *Dry-Type General Purpose and Power Transformers.*

CSA Standards

[9] CSA-C22.10-99 – *Code canadien de l'électricité, première partie (18e édition) et modification du Québec 1999*

[10] CSA-C802-94 Maximum Losses for Distribution Power and Dry-Type Transformers.

[11] CSA-C802.2-06 Minimum efficiency values for Dry-Type Transformers

[12] CSA C9-M1981, *Guide for loading Dry-Type Distribution and Power Transformers.*

IEC Standards

[13] IEC 60076 Power Transformers 1978

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[16] ROY, G., *Electronique industrielle : Notes de cours.* Montréal : École Polytechnique. 1995. ch.5,6, et 10.

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[17] M.I.T, "*MAFNETIC CIRCUITS AND TRANSFORMERS*", 1943

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Appendix 1

HOT RESISTANCES MEASURED OF ALUMINUM TRANSFORMER

Hot resistances measured from short circuit test

$AL_{Sc@50\%}$	Windings(mΩ)						Temperature (° C)					
TIME(s)	"Rp1"	"Rp2"	"Rp3"	"Rs1"	"Rs2"	"Rs3"	"coil-1"	"coil-2"	"coil-3"	"core-1"	"core-2"	"core-3"
0	291.5	291.5	290.0	9.1	9.1	9.1	35.8	36.6	35.9	31.8	32.3	31.8
27	290.8	290.8	289.1	9.1	9.1	9.1	35.6	36.7	36.0	31.9	32.3	31.9
37	290.6	290.6	289.0	9.1	9.1	9.1	35.6	36.7	35.9	31.8	32.3	31.8
47	290.4	290.4	288.8	9.1	9.1	9.1	35.5	36.6	35.9	31.8	32.3	31.9
57	290.2	290.2	288.7	9.1	9.1	9.1	35.5	36.7	35.9	31.8	32.3	31.8
67	290.0	290.0	288.5	9.1	9.0	9.1	35.5	36.6	35.8	31.8	32.2	31.8
77	289.8	289.8	288.3	9.1	9.1	9.1	35.5	36.6	35.8	31.8	32.3	31.8
87	289.6	289.6	288.3	9.1	9.0	9.0	35.4	36.5	35.7	31.8	32.3	31.8
97	289.5	289.5	288.1	9.1	9.0	9.0	35.4	36.5	35.7	31.8	32.2	31.8
107	289.5	289.5	288.0	9.0	9.0	9.0	35.3	36.5	35.7	31.8	32.2	31.8
117	289.4	289.4	288.0	9.0	9.0	9.0	35.3	36.4	35.6	31.8	32.2	31.8

Hot winding resistance of aluminum transformer measured at 50% as nominal load current from short circuit test

$AL_{Sc@60\%}$	Windings(mΩ)						Temperature (° C)					
TIME(s)	"Rp1"	"Rp2"	"Rp3"	"Rs1"	"Rs2"	"Rs3"	"coil-1"	"coil-2"	"coil-3"	"core-1"	"core-2"	"core-3"
0	301.2	301.2	299.8	9.4	9.4	9.4	41.5	43.4	43.1	37.1	37.9	37.4
27	300.2	300.2	298.8	9.3	9.4	9.4	42.3	43.8	42.9	37.1	37.9	37.2
37	299.9	299.9	298.6	9.4	9.4	9.4	42.3	43.7	43.0	37.1	37.9	37.2
47	299.8	299.8	298.4	9.3	9.4	9.4	42.1	43.7	42.9	37.1	37.8	37.2
57	299.5	299.6	298.2	9.4	9.3	9.4	42.2	43.6	42.9	37.1	37.9	37.2
67	299.4	299.4	298.0	9.4	9.3	9.4	42.1	43.6	42.8	37.2	37.8	37.3
77	299.2	299.2	297.8	9.4	9.3	9.4	42.0	43.5	42.7	37.1	37.8	37.2
87	299.1	299.1	297.7	9.3	9.3	9.3	42.0	43.5	42.7	37.1	37.9	37.3
97	298.9	298.9	297.5	9.3	9.3	9.3	41.9	43.5	42.6	37.1	37.8	37.3
107	298.9	298.9	297.5	9.3	9.3	9.3	42.0	43.4	42.7	37.1	37.8	37.2
117	298.7	298.8	297.3	9.3	9.3	9.3	41.9	43.4	42.5	37.1	37.8	37.3

Hot winding resistance of aluminum transformer measured at60% as nominal load current from short circuit test

$AL_{Sc@70\%}$	Windings(mΩ)						Temperature (° C)					
TIME(s)	"Rp1"	"Rp2"	"Rp3"	"Rs1"	"Rs2"	"Rs3"	"coil-1"	"coil-2"	"coil-3"	"core-1"	"core-2"	"core-3"
0	310.7	310.7	309.1	9.7	9.7	9.7	50.4	51.6	50.6	42.4	43.4	42.5
25	309.7	309.7	308.1	9.7	9.7	9.7	49.5	51.5	50.6	42.3	43.3	42.5
35	309.5	309.5	307.9	9.7	9.7	9.7	49.5	51.4	50.6	42.3	43.3	42.5
45	309.3	309.2	307.7	9.6	9.7	9.7	49.4	51.4	50.5	42.3	43.3	42.4
55	309.1	309.1	307.5	9.6	9.7	9.7	49.4	51.3	50.4	42.4	43.3	42.5
65	308.9	308.9	307.3	9.6	9.7	9.7	49.3	51.2	50.4	42.3	43.3	42.5
75	308.6	308.6	307.0	9.6	9.7	9.7	49.2	51.1	50.3	42.3	43.3	42.5
85	308.4	308.4	306.9	9.6	9.7	9.7	49.1	51.1	50.3	42.3	43.3	42.5
95	308.3	308.3	306.7	9.6	9.7	9.7	49.1	51.0	50.3	42.3	43.3	42.4
105	308.1	308.0	306.5	9.6	9.6	9.7	49.0	51.0	50.3	42.3	43.2	42.5
115	307.8	307.8	306.3	9.6	9.6	9.7	48.9	50.9	50.2	42.2	43.3	42.4

Hot winding resistance of aluminum transformer measured at 70% as nominal load current from short circuit test

$AL_{Sc@80\%}$	Windings(mΩ)						Temperature (° C)					
TIME(s)	"Rp1"	"Rp2"	"Rp3"	"Rs1"	"Rs2"	"Rs3"	"coil-1"	"coil-2"	"coil-3"	"core-1"	"core-2"	"core-3"
0	321.3	321.3	318.7	10.0	10.1	10.1	57.4	59.3	58.3	47.8	49.3	48.2
27	320.1	320.2	318.2	10.0	10.0	10.1	56.3	59.2	58.0	47.7	49.2	48.1
37	319.9	319.8	317.9	10.0	10.0	10.0	56.2	59.1	58.0	47.7	49.2	48.1
47	319.6	319.6	317.7	10.0	10.0	10.0	56.1	59.1	58.0	47.7	49.2	48.1
57	319.4	319.4	317.5	9.9	10.0	10.0	56.1	59.0	57.9	47.7	49.2	48.1
67	319.1	319.1	317.2	10.0	10.0	10.0	56.0	58.8	57.8	47.7	49.2	48.1
77	318.8	318.9	316.9	10.0	10.0	10.0	55.9	58.8	57.6	47.7	49.2	48.1
87	318.6	318.7	316.8	9.9	10.0	10.0	55.8	58.7	57.5	47.7	49.2	48.1
97	318.5	318.5	316.6	9.9	10.0	10.0	55.7	58.6	57.5	47.7	49.2	48.1
107	318.3	318.3	316.4	9.9	10.0	10.0	55.6	58.6	57.4	47.7	49.2	48.1
117	318.1	318.2	316.2	9.9	10.0	10.0	55.5	58.4	57.3	47.7	49.2	48.1

Hot winding resistance of aluminum transformer measured at 80% as nominal load current from short circuit test

$AL_{Sc@90\%}$	Windings(mΩ)						Temperature (° C)					
TIME(s)	"Rp1"	"Rp2"	"Rp3"	"Rs1"	"Rs2"	"Rs3"	"coil-1"	"coil-2"	"coil-3"	"core-1"	"core-2"	"core-3"
0	332.3	332.3	329.4	10.3	10.4	10.4	63.9	67.5	66.2	53.2	55.2	53.9
25	331.1	331.0	329.1	10.3	10.4	10.4	63.3	67.0	65.8	53.1	55.1	53.8
35	330.7	330.7	328.7	10.3	10.4	10.4	63.3	66.9	65.7	53.1	55.1	53.8
45	330.5	330.4	328.5	10.3	10.4	10.4	63.1	66.8	65.6	53.1	55.1	53.8
55	330.2	330.2	328.2	10.3	10.4	10.4	62.9	66.7	65.5	53.1	55.1	53.8
65	329.8	329.9	327.9	10.3	10.4	10.4	62.8	66.5	65.5	53.0	55.1	53.7
75	329.7	329.7	327.6	10.3	10.4	10.4	62.8	66.4	65.4	53.1	55.2	53.8
85	329.4	329.4	327.4	10.3	10.4	10.4	62.7	66.3	65.4	53.0	55.2	53.8
95	329.2	329.2	327.2	10.2	10.4	10.3	62.6	66.2	65.3	53.1	55.1	53.8
105	328.9	328.9	326.9	10.3	10.3	10.4	62.5	66.0	65.2	53.1	55.2	53.8
115	328.6	328.6	326.6	10.3	10.3	10.3	62.3	65.9	65.0	53.1	55.0	53.7

Hot winding resistance of aluminum transformer measured at 90% as nominal load current from short circuit test

$AL_{Sc@100\%}$	Windings(mΩ)						Temperature (° C)					
TIME(s)	"Rp1"	"Rp2"	"Rp3"	"Rs1"	"Rs2"	"Rs3"	"coil-1"	"coil-2"	"coil-3"	"core-1"	"core-2"	"core-3"
0	345.5	345.5	342.0	10.8	10.9	10.9	72.6	77.5	75.5	60.0	62.6	60.7
28	344.7	344.8	341.7	10.8	10.9	10.8	72.1	77.0	75.2	59.9	62.6	60.7
38	344.5	344.5	341.4	10.7	10.9	10.8	72.0	76.9	75.1	59.8	62.6	60.7
48	344.0	344.0	341.1	10.7	10.8	10.8	71.8	76.8	74.9	59.8	62.6	60.7
58	343.7	343.7	340.8	10.7	10.8	10.8	71.7	76.7	74.8	59.9	62.5	60.7
68	343.5	343.5	340.5	10.7	10.8	10.8	71.5	76.5	74.7	59.8	62.5	60.7
78	343.1	343.1	340.2	10.7	10.8	10.8	71.4	76.4	74.5	59.8	62.5	60.7
88	342.9	342.9	339.9	10.7	10.8	10.8	71.2	76.2	74.4	59.8	62.5	60.7
98	342.5	342.5	339.6	10.7	10.8	10.8	71.0	76.0	74.2	59.8	62.5	60.6
108	342.2	342.2	339.3	10.7	10.8	10.8	70.9	75.9	74.1	59.8	62.5	60.7
118	342.1	342.1	339.1	10.6	10.8	10.7	70.8	75.8	73.9	59.8	62.5	60.7

Hot winding resistance of aluminum transformer measured at 100% as nominal load current from short circuit test

Hot resistances measured from back to back test

$Al_{bb@50\%}$	Windings(mΩ)						Temperature (° C)					
TIME(s)	"Rp1"	"Rp2"	"Rp3"	"Rs1"	"Rs2"	"Rs3"	"coil-1"	"coil-2"	"coil-3"	"core-1"	"core-2"	"core-3"
0	310.0	310.0	307.4	9.9	9.9	9.9	48.4	50.9	48.5	72.5	77.9	73.3
30	309.8	309.8	306.9	9.9	9.8	9.8	48.4	50.9	48.3	72.4	77.9	73.3
40	309.6	309.6	306.9	9.9	9.8	9.8	48.4	50.8	48.4	72.3	77.9	73.2
50	309.5	309.5	306.7	9.9	9.8	9.8	48.3	50.8	48.3	72.3	77.8	73.2
60	309.5	309.4	306.9	9.8	9.8	9.8	48.3	50.7	48.3	72.3	77.7	73.1
70	309.3	309.3	306.6	9.8	9.8	9.8	48.3	50.7	48.2	72.2	77.7	73.2
80	309.2	309.2	306.5	9.8	9.8	9.8	48.2	50.8	48.2	72.2	77.7	73.1
90	309.1	309.0	306.5	9.8	9.8	9.8	48.3	50.7	48.2	72.1	77.6	73.0
100	308.8	308.9	306.3	9.8	9.8	9.8	48.2	50.7	48.2	72.1	77.5	73.1
110	308.8	308.8	306.1	9.8	9.8	9.8	48.2	50.7	48.1	72.0	77.5	73.0
120	308.8	308.8	306.1	9.8	9.8	9.8	48.2	50.6	48.2	72.0	77.4	73.0

Hot winding resistance of aluminum transformer measured at 50% as nominal load current from back to back test

$Al_{bb@60\%}$	Windings(mΩ)						Temperature (° C)					
TIME(s)	"Rp1"	"Rp2"	"Rp3"	"Rs1"	"Rs2"	"Rs3"	"coil-1"	"coil-2"	"coil-3"	"core-1"	"core-2"	"core-3"
0	316.2	316.0	314.2	10.1	10.2	10.1	51.8	55.6	52.7	74.3	80.5	75.9
24	315.7	315.8	313.1	10.0	10.1	10.0	51.7	55.3	52.6	74.1	80.2	75.8
34	315.5	315.5	312.9	10.0	10.1	10.0	51.7	55.3	52.6	74.1	80.2	75.7
44	315.3	315.3	312.8	10.0	10.1	10.0	51.6	55.2	52.6	74.0	80.1	75.7
54	315.0	315.0	312.2	10.1	10.1	10.1	51.6	55.2	52.6	74.0	80.1	75.6
64	314.9	314.9	312.4	10.0	10.1	10.0	51.5	55.2	52.6	74.0	80.1	75.6
74	314.7	314.8	312.1	10.0	10.1	10.0	51.5	55.1	52.5	73.9	80.0	75.5
84	314.6	314.6	312.1	9.9	10.1	10.0	51.4	55.1	52.5	73.9	79.9	75.5
94	314.4	314.3	311.8	10.0	10.0	10.0	51.4	55.0	52.5	73.8	79.9	75.4
104	314.2	314.2	311.5	10.0	10.0	10.0	51.4	55.0	52.5	73.8	79.8	75.3
114	314.2	314.2	311.6	10.0	10.0	10.0	51.4	54.9	52.4	73.8	79.8	75.3

Hot winding resistance of aluminum transformer measured at 60% as nominal load current from back to back test

$Al_{bb@70\%}$	Windings(mΩ)						Temperature (° C)					
TIME(s)	"Rp1"	"Rp2"	"Rp3"	"Rs1"	"Rs2"	"Rs3"	"coil-1"	"coil-2"	"coil-3"	"core-1"	"core-2"	"core-3"
0	323.5	323.5	321.0	10.4	10.4	10.3	57.8	60.9	57.9	77.7	83.9	78.9
27	322.7	322.7	320.2	10.3	10.3	10.3	57.5	60.8	57.9	77.5	83.6	78.8
37	322.4	322.4	319.9	10.3	10.3	10.3	57.5	60.7	57.9	77.4	83.6	78.8
47	322.1	322.1	319.5	10.3	10.3	10.3	57.3	60.6	57.9	77.4	83.6	78.7
57	321.9	321.9	319.3	10.3	10.3	10.3	57.3	60.5	57.8	77.3	83.5	78.7
67	321.7	321.7	319.1	10.3	10.3	10.2	57.2	60.5	57.7	77.3	83.5	78.6
77	321.4	321.4	318.9	10.3	10.3	10.2	57.1	60.5	57.7	77.2	83.4	78.7
87	321.3	321.3	318.6	10.3	10.3	10.2	57.0	60.4	57.6	77.2	83.4	78.6
97	321.0	321.0	318.5	10.3	10.3	10.2	57.0	60.4	57.5	77.2	83.3	78.5
107	320.8	320.8	318.3	10.3	10.3	10.2	57.0	60.3	57.5	77.2	83.3	78.5
117	320.6	320.7	318.1	10.3	10.2	10.2	56.9	60.3	57.4	77.2	83.2	78.5

Hot winding resistance of aluminum transformer measured at 70% as nominal load current from back to back test

$Al_{bb@80\%}$	Windings(mΩ)						Temperature (° C)					
TIME(s)	"Rp1"	"Rp2"	"Rp3"	"Rs1"	"Rs2"	"Rs3"	"coil-1"	"coil-2"	"coil-3"	"core-1"	"core-2"	"core-3"
0	331.0	331.0	327.5	10.6	10.7	10.6	61.5	65.4	61.4	78.8	85.4	80.2
24	329.2	329.4	326.2	10.5	10.5	10.4	61.4	65.1	61.3	78.8	85.2	80.3
34	328.9	329.0	325.8	10.5	10.5	10.5	61.4	65.0	61.2	78.7	85.2	80.2
44	328.6	328.6	325.0	10.5	10.5	10.5	61.2	64.9	61.1	78.7	85.0	80.0
54	328.4	328.5	324.7	10.5	10.5	10.4	61.1	64.8	61.1	78.6	84.9	79.9
64	328.1	328.1	324.5	10.5	10.5	10.4	61.0	64.8	61.0	78.7	85.0	79.8
74	327.9	327.9	324.2	10.5	10.5	10.4	60.9	64.7	60.8	78.7	84.9	79.8
84	327.7	327.7	324.0	10.4	10.5	10.4	60.8	64.6	60.8	78.8	84.9	79.6
94	327.3	327.3	323.8	10.5	10.5	10.4	60.7	64.5	60.7	78.8	84.8	79.7
104	327.2	327.2	323.6	10.4	10.5	10.4	60.6	64.4	60.6	78.7	84.7	79.6
114	326.9	326.9	323.3	10.5	10.5	10.4	60.6	64.4	60.6	78.6	84.7	79.5

Hot winding resistance of aluminum transformer measured at 80% as nominal load current from back to back test

$Al_{bb@90\%}$	Windings(mΩ)						Temperature (° C)					
TIME(s)	"Rp1"	"Rp2"	"Rp3"	"Rs1"	"Rs2"	"Rs3"	"coil-1"	"coil-2"	"coil-3"	"core-1"	"core-2"	"core-3"
0	341.4	341.4	338.5	10.9	11.0	10.9	68.5	72.6	68.6	83.5	90.1	84.7
27	338.7	338.9	335.8	10.8	10.9	10.8	68.4	72.4	68.4	83.4	90.0	84.7
37	338.4	338.6	335.2	10.8	10.8	10.8	68.2	72.3	68.3	83.4	90.0	84.7
47	338.2	338.2	335.0	10.8	10.9	10.8	68.2	72.2	68.3	83.4	90.0	84.6
57	337.9	337.9	334.5	10.8	10.8	10.8	68.0	72.1	68.1	83.3	89.9	84.6
67	337.7	337.7	334.3	10.8	10.8	10.8	67.9	72.0	68.1	83.3	89.8	84.4
77	337.5	337.5	334.0	10.8	10.8	10.7	67.7	71.9	68.0	83.2	89.9	84.5
87	337.2	337.2	333.7	10.8	10.8	10.7	67.6	71.7	67.9	83.2	89.8	84.5
97	336.9	336.8	333.5	10.8	10.8	10.7	67.5	71.6	67.8	83.2	89.7	84.5
107	336.6	336.7	333.3	10.8	10.8	10.7	67.5	71.5	67.7	83.2	89.6	84.4
117	336.6	336.6	333.1	10.7	10.8	10.7	67.3	71.4	67.6	83.1	89.6	84.3

Hot winding resistance of aluminum transformer measured at 90% as nominal load current from back to back test

$Al_{bb@100\%}$	Windings(mΩ)						Temperature (° C)					
TIME(s)	"Rp1"	"Rp2"	"Rp3"	"Rs1"	"Rs2"	"Rs3"	"coil-1"	"coil-2"	"coil-3"	"core-1"	"core-2"	"core-3"
0	352.6	352.6	348.7	11.3	11.4	11.3	75.5	80.1	75.6	87.5	94.4	88.6
26	349.4	349.7	346.0	11.2	11.2	11.1	75.3	80.1	75.5	87.4	94.4	88.7
36	349.1	349.1	345.5	11.2	11.2	11.1	75.1	79.9	75.4	87.3	94.2	88.6
46	348.5	348.6	344.8	11.1	11.2	11.1	75.1	79.8	75.2	87.2	94.1	88.5
56	348.2	348.3	344.5	11.1	11.2	11.1	74.8	79.6	75.1	87.3	94.1	88.5
66	348.3	348.1	344.2	11.1	11.2	11.1	74.7	79.6	75.0	87.2	94.0	88.4
76	347.8	347.8	343.9	11.1	11.2	11.1	74.6	79.4	75.0	87.1	94.1	88.4
86	347.5	347.5	343.6	11.1	11.2	11.1	74.5	79.2	74.8	87.1	93.9	88.4
96	347.1	347.1	343.3	11.1	11.1	11.1	74.4	79.1	74.7	87.1	93.9	88.4
106	346.8	346.8	343.0	11.1	11.1	11.1	74.2	78.9	74.5	87.1	93.9	88.2
116	346.6	346.6	342.8	11.0	11.1	11.0	73.9	78.6	74.4	87.0	93.8	88.1

Hot winding resistance of aluminum transformer measured at 100% as nominal load current from back to back test

Appendix 2

HOT RESISTANCES MEASURED OF COPPER TRANSFORMER

Hot resistances measured from short circuit test

$CP_{Sc@5\%}$	Windings(mΩ)						Temperature (° C)					
TIME(s)	"Rp1"	"Rp2"	"Rp3"	"Rs1"	"Rs2"	"Rs3"	"coil-1"	"coil-2"	"coil-3"	"core-1"	"core-2"	"core-3"
0	477.4	477.4	470.8	10.8	10.9	10.7	45.3	46.4	44.9	39.2	37.1	36.8
13	476.9	476.9	470.2	10.8	10.8	10.6	45.5	46.2	45.1	37.8	37.1	36.9
23	476.6	476.5	469.8	10.8	10.8	10.6	45.5	46.1	45.1	37.5	37.2	36.8
33	476.2	476.1	469.4	10.7	10.8	10.6	45.4	46.0	44.9	37.7	37.2	36.8
43	475.8	475.8	469.0	10.7	10.8	10.6	45.2	45.9	44.9	37.3	37.1	36.8
53	475.4	475.4	468.8	10.8	10.8	10.6	45.3	45.8	44.8	36.1	37.1	36.8
63	475.0	475.0	468.3	10.7	10.8	10.6	45.2	45.7	44.7	36.3	37.1	36.8
73	474.7	474.7	468.1	10.8	10.8	10.6	45.1	45.5	44.6	36.5	37.1	36.8
83	474.4	474.3	467.8	10.7	10.8	10.6	45.0	45.4	44.6	36.6	37.2	36.9
93	474.0	474.0	467.3	10.7	10.8	10.5	44.9	45.3	44.4	37.1	37.1	36.8
103	473.8	473.8	467.1	10.7	10.8	10.6	44.7	45.3	44.4	37.5	37.2	36.8

Hot winding resistance of copper transformer measured at 50% as nominal load current from short circuit test

$CP_{Sc@60\%}$	Windings(mΩ)						Temperature (° C)					
TIME(s)	"Rp1"	"Rp2"	"Rp3"	"Rs1"	"Rs2"	"Rs3"	"coil-1"	"coil-2"	"coil-3"	"core-1"	"core-2"	"core-3"
0	494.4	494.4	485.8	11.1	11.2	11.0	54.0	58.6	53.5	40.6	41.3	40.8
14	493.4	493.3	484.7	11.1	11.2	10.9	53.8	58.4	52.9	40.6	41.3	40.8
24	492.8	492.8	484.2	11.1	11.2	10.9	53.8	58.3	53.0	40.6	41.3	40.8
34	492.3	492.3	483.6	11.0	11.2	10.9	53.6	58.1	52.9	40.7	41.3	40.8
44	491.8	491.7	483.1	11.0	11.2	10.9	53.4	58.0	52.7	40.7	41.3	40.9
54	491.3	491.2	482.6	11.0	11.1	10.8	53.3	57.8	52.3	40.6	41.3	40.8
64	490.8	490.7	482.1	11.0	11.1	10.8	53.1	57.7	52.3	40.7	41.3	40.8
74	490.3	490.3	481.8	11.0	11.1	10.9	53.1	57.4	52.1	40.7	41.4	40.8
84	489.9	490.0	481.4	11.0	11.1	10.9	52.8	57.2	52.0	40.7	41.3	40.8
94	489.5	489.4	480.8	11.0	11.1	10.8	52.7	57.1	52.0	40.7	41.3	40.8
104	489.1	489.0	480.4	11.0	11.1	10.8	52.6	56.9	51.8	40.7	41.3	40.8

Hot winding resistance of copper transformer measured at 60% as nominal load current from short circuit test

CP$_{Sc@70\%}$	Windings(mΩ)						Temperature (° C)					
TIME(s)	"Rp1"	"Rp2"	"Rp3"	"Rs1"	"Rs2"	"Rs3"	"coil-1"	"coil-2"	"coil-3"	"core-1"	"core-2"	"core-3"
0	508.8	508.8	498.3	11.4	11.5	11.3	61.1	66.7	59.9	46.1	47.1	46.0
14	507.7	507.7	497.2	11.3	11.5	11.2	60.7	66.7	59.4	46.2	47.1	45.8
24	507.0	507.0	496.5	11.3	11.5	11.1	60.5	66.5	59.3	46.2	47.1	45.9
34	506.3	506.3	495.9	11.3	11.5	11.1	60.5	66.2	59.1	46.2	47.1	45.8
44	505.8	505.7	495.5	11.3	11.4	11.1	60.3	66.0	59.0	46.2	47.1	45.8
54	505.1	505.1	494.8	11.3	11.4	11.1	60.1	65.8	58.8	46.2	47.1	45.8
64	504.5	504.5	494.1	11.3	11.4	11.1	59.8	65.5	58.5	46.1	47.1	45.8
74	503.9	503.9	493.7	11.3	11.4	11.1	59.7	65.3	58.5	46.2	47.1	45.9
84	503.4	503.4	493.2	11.3	11.4	11.1	59.6	65.1	58.4	46.2	47.1	45.8
94	502.8	502.8	492.6	11.3	11.4	11.1	59.5	64.8	58.1	46.1	47.1	45.8
104	502.3	502.3	492.1	11.3	11.4	11.1	59.4	64.6	58.0	46.2	47.1	45.8

Hot winding resistance of copper transformer measured at 70% as nominal load current from short circuit test

CP$_{Sc@80\%}$	Windings(mΩ)						Temperature (° C)					
TIME(s)	"Rp1"	"Rp2"	"Rp3"	"Rs1"	"Rs2"	"Rs3"	"coil-1"	"coil-2"	"coil-3"	"core-1"	"core-2"	"core-3"
0	531.0	531.0	519.2	11.9	12.0	11.7	73.3	79.6	71.3	53.0	54.1	52.1
14	529.9	529.9	518.3	11.8	11.9	11.6	73.2	79.3	71.3	53.2	54.1	52.1
24	529.0	529.1	517.3	11.8	11.9	11.6	72.9	79.1	70.9	53.2	54.1	52.2
34	528.2	528.2	516.5	11.8	11.9	11.6	72.6	78.8	70.6	53.2	54.1	52.1
44	527.5	527.4	515.8	11.8	11.9	11.6	72.2	78.5	70.3	53.2	54.1	52.2
54	526.6	526.6	514.8	11.8	11.9	11.6	71.9	78.1	70.1	53.2	54.1	52.1
64	525.9	525.9	514.3	11.8	11.9	11.6	71.6	77.8	69.9	53.2	54.1	52.1
74	525.1	525.1	513.6	11.8	11.8	11.6	71.3	77.5	69.7	53.2	54.0	52.1
84	524.3	524.3	512.7	11.7	11.8	11.5	71.0	77.2	69.4	53.2	54.1	52.1
94	523.7	523.6	511.9	11.7	11.8	11.5	70.7	76.9	69.1	53.1	54.1	52.1
104	523.0	523.0	511.5	11.8	11.8	11.5	70.5	76.6	68.8	53.1	54.1	52.1

Hot winding resistance of copper transformer measured at 80% as nominal load current from short circuit test

CP$_{Sc@90\%}$	Windings(mΩ)						Temperature (° C)					
TIME(s)	"Rp1"	"Rp2"	"Rp3"	"Rs1"	"Rs2"	"Rs3"	"coil-1"	"coil-2"	"coil-3"	"core-1"	"core-2"	"core-3"
0	554.1	554.1	539.5	12.3	12.4	12.1	83.6	93.1	82.2	59.8	61.5	58.8
16	552.1	552.1	537.6	12.2	12.4	12.0	83.6	92.6	81.9	59.8	61.5	58.7
26	551.0	550.9	536.5	12.2	12.4	12.0	83.3	92.2	81.6	59.8	61.5	58.8
36	550.0	550.0	535.7	12.2	12.4	12.0	83.0	91.8	81.2	59.8	61.5	58.8
46	548.9	548.8	534.5	12.2	12.3	12.0	82.5	91.4	81.0	59.8	61.5	58.8
56	547.9	547.9	533.6	12.2	12.3	12.0	82.1	90.9	80.7	59.8	61.5	58.8
66	546.9	547.0	532.9	12.2	12.3	12.0	81.6	90.5	80.5	59.8	61.5	58.8
76	546.0	546.0	531.9	12.2	12.3	12.0	81.7	90.1	80.0	59.8	61.5	58.8
86	545.0	545.0	530.9	12.1	12.3	11.9	81.4	89.7	79.7	59.8	61.5	58.8
96	544.2	544.1	530.2	12.1	12.3	12.0	80.9	89.3	79.2	59.9	61.4	58.8
106	543.3	543.3	529.3	12.1	12.3	11.9	80.6	88.9	78.8	59.9	61.5	58.7

Hot winding resistance of copper transformer measured at90% as nominal load current from short circuit test

CP$_{Sc@100\%}$	Windings(mΩ)						Temperature (° C)					
TIME(s)	"Rp1"	"Rp2"	"Rp3"	"Rs1"	"Rs2"	"Rs3"	"coil-1"	"coil-2"	"coil-3"	"core-1"	"core-2"	"core-3"
0	579.9	579.9	562.8	12.9	13.0	12.6	96.1	108.0	95.5	68.8	71.1	579.9
15	578.6	578.6	561.8	12.8	12.9	12.6	95.8	107.4	95.3	68.7	71.2	578.6
25	577.0	577.0	560.2	12.7	12.9	12.5	95.3	106.9	95.2	68.7	71.2	577.0
35	575.7	575.7	559.0	12.7	12.9	12.5	94.8	106.4	94.7	68.8	71.2	575.7
45	574.4	574.5	557.7	12.7	12.9	12.5	94.4	105.8	94.2	68.7	71.2	574.4
55	573.3	573.2	556.7	12.7	12.9	12.5	93.9	105.3	93.6	68.7	71.2	573.3
65	572.1	572.0	555.6	12.7	12.9	12.5	93.3	104.8	93.1	68.7	71.2	572.1
75	570.9	570.9	554.5	12.7	12.8	12.5	92.9	104.2	92.6	68.7	71.2	570.9
85	569.8	569.8	553.4	12.6	12.8	12.5	92.4	103.6	92.0	68.7	71.1	569.8
95	568.7	568.6	552.3	12.6	12.8	12.4	91.9	103.1	91.2	68.7	71.1	568.7
105	567.6	567.6	551.3	12.6	12.8	12.4	91.4	102.5	91.0	68.7	71.1	567.6

Hot winding resistance of copper transformer measured at 100% as nominal load current from short circuit test

Hot resistances measured from back to back test

$CP_{bb@50\%}$	Windings(mΩ)						Temperature (° C)					
TIME(s)	"Rp1"	"Rp2"	"Rp3"	"Rs1"	"Rs2"	"Rs3"	"coil-1"	"coil-2"	"coil-3"	"core-1"	"core-2"	"core-3"
0	489.1	489.1	481.4	11.4	11.5	11.3	50.7	53.4	50.4	72.2	76.7	67.9
8	488.6	488.6	480.0	11.4	11.5	11.3	50.2	53.1	50.1	72.0	76.5	67.2
18	488.0	488.0	479.4	11.4	11.5	11.2	50.7	53.4	50.4	72.2	76.7	67.9
28	487.4	487.3	478.8	11.4	11.5	11.2	50.0	53.1	50.2	72.0	76.5	67.5
38	486.9	486.9	478.4	11.4	11.5	11.2	49.9	53.0	50.2	72.0	76.5	67.5
48	486.6	486.6	478.1	11.4	11.5	11.1	49.8	52.9	50.1	72.0	76.5	67.4
58	486.2	486.2	477.7	11.4	11.4	11.2	49.7	52.8	50.2	71.9	76.4	67.5
68	485.8	485.8	477.4	11.4	11.4	11.1	49.6	52.7	50.2	71.9	76.4	67.5
78	485.5	485.5	477.0	11.4	11.4	11.2	49.7	52.7	50.1	71.8	76.4	67.5
88	485.2	485.2	476.7	11.4	11.4	11.1	49.8	52.7	49.9	71.8	76.3	67.5
98	484.9	484.9	476.4	11.3	11.4	11.1	49.7	52.5	49.9	71.8	76.3	67.5

Hot winding resistance of copper transformer measured at 50% as nominal load current from back to back test

$CP_{bb@60\%}$	Windings(mΩ)						Temperature (° C)					
TIME(s)	"Rp1"	"Rp2"	"Rp3"	"Rs1"	"Rs2"	"Rs3"	"coil-1"	"coil-2"	"coil-3"	"core-1"	"core-2"	"core-3"
0	507.5	507.5	496.8	11.8	11.9	11.7	60.5	64.4	60.8	78.3	82.9	75.1
24	505.9	505.8	495.2	11.8	11.9	11.6	60.4	64.2	60.7	78.2	82.8	74.7
34	505.4	505.3	494.6	11.8	11.9	11.6	60.3	64.0	60.6	78.2	82.7	74.6
44	504.8	504.8	494.3	11.8	11.8	11.5	60.1	63.9	60.4	78.1	82.7	74.6
54	504.4	504.4	493.7	11.8	11.8	11.5	59.9	63.8	60.2	78.1	82.6	74.5
64	503.8	503.8	493.3	11.8	11.8	11.5	59.8	63.6	60.0	78.0	82.5	74.5
74	503.5	503.4	492.9	11.8	11.8	11.5	59.7	63.5	59.9	78.0	82.5	74.5
84	503.0	503.0	492.4	11.7	11.8	11.5	59.5	63.3	59.8	78.0	82.4	74.4
94	502.6	502.5	492.1	11.7	11.8	11.5	59.5	63.1	59.8	78.0	82.4	74.4
104	502.2	502.2	491.7	11.7	11.8	11.5	59.3	63.1	59.7	77.9	82.4	74.4
114	501.7	501.7	491.3	11.7	11.8	11.5	59.2	62.9	59.6	77.8	82.3	74.3

Hot winding resistance of copper transformer measured at 60% as nominal load current from back to back test

$CP_{bb@70\%}$	Windings(mΩ)						Temperature (° C)					
TIME(s)	"Rp1"	"Rp2"	"Rp3"	"Rs1"	"Rs2"	"Rs3"	"coil-1"	"coil-2"	"coil-3"	"core-1"	"core-2"	"core-3"
0	525.0	525.1	513.0	12.1	12.2	11.9	68.7	74.4	69.4	82.1	86.8	77.7
27	522.7	522.7	509.8	12.1	12.2	11.9	68.5	73.8	69.2	81.9	86.7	78.0
37	522.1	522.1	508.6	12.1	12.2	11.8	68.3	73.7	68.9	81.9	86.7	77.9
47	521.4	521.5	507.7	12.1	12.2	11.8	68.1	73.5	68.7	81.9	86.7	77.9
57	520.7	520.7	507.1	12.1	12.2	11.8	67.8	73.2	68.4	81.8	86.6	77.9
67	520.1	520.1	506.5	12.1	12.2	11.8	67.7	73.1	68.3	81.8	86.6	77.8
77	519.5	519.5	506.0	12.1	12.1	11.8	67.6	72.8	68.2	81.7	86.6	77.8
87	518.9	518.9	505.4	12.1	12.1	11.8	67.4	72.6	68.1	81.7	86.4	77.7
97	518.4	518.3	504.9	12.0	12.1	11.8	67.2	72.5	67.8	81.6	86.3	77.7
107	517.8	517.9	504.4	12.0	12.1	11.7	67.2	72.3	67.7	81.6	86.3	77.7
117	517.2	517.2	503.8	12.0	12.1	11.8	67.0	72.1	67.5	81.6	86.2	77.6

Hot winding resistance of copper transformer measured at 70% as nominal load current from back to back test

$CP_{bb@80\%}$	Windings(mΩ)						Temperature (° C)					
TIME(s)	"Rp1"	"Rp2"	"Rp3"	"Rs1"	"Rs2"	"Rs3"	"coil-1"	"coil-2"	"coil-3"	"core-1"	"core-2"	"core-3"
0	543.2	543.6	530	12.5	12.6	12.2	78.7	84.8	80.4	87.0	91.9	83.0
25	539.6	539.7	525.3	12.4	12.6	12.2	78.2	84.1	79.9	87.0	92.0	82.8
35	538.9	538.8	524.6	12.4	12.5	12.2	78.0	83.8	79.6	86.9	91.9	82.7
45	537.9	537.9	523.7	12.4	12.5	12.2	77.7	83.6	79.4	86.9	91.9	82.7
55	537.1	537.1	523.0	12.4	12.5	12.1	77.4	83.2	79.1	86.8	91.8	82.7
65	536.4	536.4	522.3	12.4	12.5	12.1	77.2	82.9	78.7	86.8	91.8	82.7
75	535.6	535.6	521.5	12.4	12.5	12.1	76.9	82.7	78.6	86.8	91.8	82.7
85	534.8	534.9	520.8	12.4	12.5	12.1	76.7	82.4	78.3	86.7	91.7	82.6
95	534.2	534.2	520.2	12.3	12.5	12.1	76.4	82.2	78.1	86.6	91.6	82.5
105	533.4	533.5	519.5	12.3	12.5	12.1	76.2	81.9	77.8	86.6	91.5	82.4
115	532.8	532.8	518.9	12.3	12.4	12.1	76.0	81.5	77.5	86.6	91.5	82.4

Hot winding resistance of copper transformer measured at 80% as nominal load current from back to back test

$CP_{bb@90\%}$	Windings(mΩ)						Temperature (° C)					
TIME(s)	"Rp1"	"Rp2"	"Rp3"	"Rs1"	"Rs2"	"Rs3"	"coil-1"	"coil-2"	"coil-3"	"core-1"	"core-2"	"core-3"
0	563.2	563.2	547.4	12.9	13.0	12.7	90.4	97.0	91.3	92.6	98.0	88.5
26	559.6	559.6	544.9	12.9	13.0	12.6	89.9	96.2	90.6	92.6	97.9	87.7
36	558.6	558.6	541.9	12.9	12.9	12.6	89.5	95.8	90.2	92.6	97.9	87.7
46	557.5	557.5	541.0	12.9	12.9	12.6	89.1	95.5	89.8	92.5	97.8	87.6
56	556.6	556.6	540.3	12.8	12.9	12.5	88.8	95.0	89.4	92.5	97.8	87.6
66	555.5	555.6	539.1	12.8	12.9	12.5	88.4	94.7	89.0	92.4	97.8	87.5
76	554.5	554.5	538.3	12.8	12.9	12.5	88.1	94.2	88.6	92.4	97.6	87.5
86	553.6	553.6	537.5	12.8	12.8	12.5	87.8	94.0	88.3	92.3	97.6	87.4
96	552.7	552.7	536.6	12.8	12.8	12.5	87.3	93.5	87.8	92.2	97.5	87.4
106	551.8	551.8	535.8	12.8	12.8	12.4	86.9	93.2	87.5	92.2	97.5	87.4
116	551.0	551.0	534.9	12.7	12.8	12.4	86.5	92.7	87.2	92.2	97.5	87.3

Hot winding resistance of copper transformer measured at 90% as nominal load current from back to back test

$CP_{bb@100\%}$	Windings(mΩ)						Temperature (° C)					
TIME(s)	"Rp1"	"Rp2"	"Rp3"	"Rs1"	"Rs2"	"Rs3"	"coil-1"	"coil-2"	"coil-3"	"core-1"	"core-2"	"core-3"
0	591.6	591.7	571.8	13.4	13.6	13.1	104.9	113.5	105.9	100.2	106.3	95.1
28	585.9	585.9	565.8	13.3	13.5	13.0	104.0	112.0	104.8	100.0	106.1	95.3
38	584.6	584.6	564.6	13.4	13.5	13.0	103.5	111.3	104.3	100.0	106.1	95.2
48	583.4	583.4	563.4	13.3	13.5	13.0	103.1	110.9	103.6	100.0	106.1	95.2
58	582.0	582.0	562.1	13.3	13.4	13.0	102.5	110.4	103.2	99.9	106.0	95.2
68	580.8	580.9	561.0	13.3	13.4	13.0	101.9	109.7	102.6	99.9	105.9	95.1
78	579.5	579.6	559.9	13.3	13.4	13.0	101.3	109.4	102.1	99.8	105.9	95.0
88	578.4	578.4	558.8	13.3	13.4	13.0	100.9	108.7	101.8	99.7	105.8	95.0
98	577.3	577.3	557.7	13.2	13.4	12.9	100.5	108.3	101.2	99.7	105.8	95.0
108	576.1	576.2	556.7	13.3	13.4	12.9	100.0	107.9	100.9	99.6	105.7	94.9
118	575.2	575.2	555.8	13.2	13.4	12.9	99.7	107.5	100.4	99.6	105.6	94.8

Hot winding resistance of copper transformer measured at 100% as nominal load current from back to back test

Appendix 3

TECHNICAL DATA SHEET

BEMAG.ca
TRANSFORMATEUR TRANSFORMER

TEL : (450) 293-8998, (800) 822-3565 FAX : (450) 293-8999 WEB : WWW.BEMAG.CA

TECHNICAL DATA : UA3030VR115.

DESCRIPTION	
Type	DRY TYPE DISTRIBUTION
KVA	30
Primary (Volts)	600
Secondary (Volts)	120 / 208
Phase	3
Enclosure NEMA	NEMA 2
Impedance	2.4 %
Temp. Rise	115°C
Temp. Class	220°C
Frequency	60 Hz
K Factor	1
Weight	362 Lbs / 165 Kg

PERFORMANCES	
No Load loss	207 Watts
Load loss 135°C	535.6 Watts
Load loss per C802 (35%)	70.5 Watts
Total loss	742.6 Watts
Excitation current	2.91 %
Noise level	45 DB
Impedance from secondary	0.06 Ohm (Line To Line)

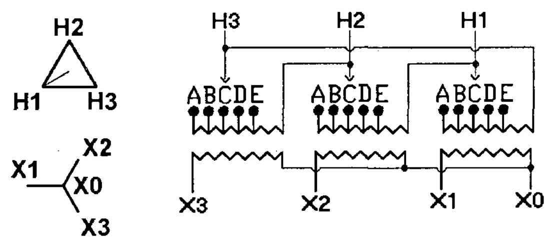
% EFFICIENCY (AT 35% FULL LOAD)		% REGULATION (FULL LOAD)			
Minimum per C802	97.50	1.00	0.95	0.90	0.85
Estimated	97.56	1.80%	2.20%	2.31%	2.37%

TAPS

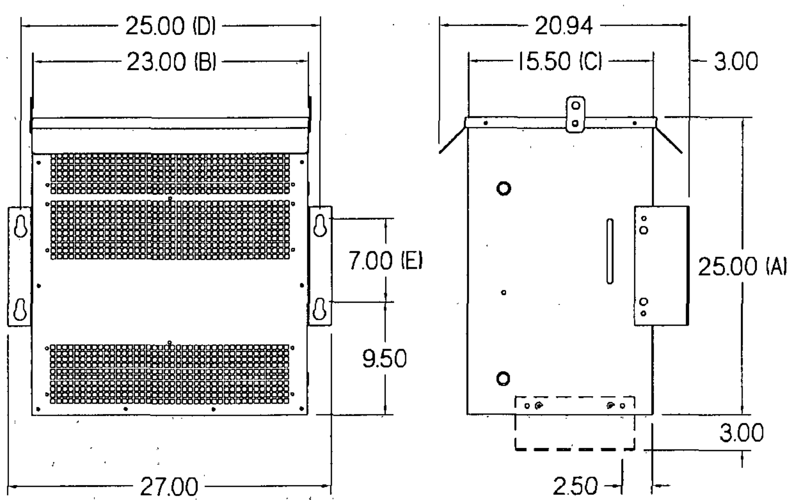
Pos	A	B	C	D	E	F	G
%	+5	+2.5	0	-2.5	-5		
Volts	630	615	600	585	570		

Primary connectors by phase 1 #2 AWG - #14 AWG
Secondary connectors by phase 1 250 MCM
Primary Winding in Aluminium
Secondary Winding in Aluminium

CONNECTION DIAGRAM



PHYSICAL DIMENSIONS



ENCLOSURE		
	INCHES	MM
A	25	635
B	23	584
C	15.5	394
D	25	635
E	7	178

MOUNTING : WALL AND FLOOR

		COMMENTS
Customer / PO	ECOLE POLYTECHNIQUE	
Contact	DAWEI ZHU	
Project		
Revised by	Frédérick Dubeau	

BEMAG.ca TRANSFORMATEUR TRANSFORMER

TEL : (450) 293-8998, (800) 822-3565 FAX : (450) 293-8999 WEB : WWW.BEMAG.CA

TECHNICAL DATA : UC3030VR115.

DESCRIPTION

Type	DRY TYPE DISTRIBUTION
KVA	30
Primary (Volts)	600
Secondary (Volts)	120 / 208
Phase	3
Enclosure NEMA	NEMA 2
Impedance	3.4 %
Temp. Rise	115°C
Temp. Class	220°C
Frequency	60 Hz
K Factor	1
Weight	356 Lbs / 162 Kg

PERFORMANCES

No Load loss	146.4 Watts
Load loss 135°C	796.4 Watts
Load loss per C802 (35%)	103.0 Watts
Total loss	942.8 Watts
Excitation current	2.35 %
Noise level	45 DB
Impedance from secondary	0.084 Ohm (Line To Line)

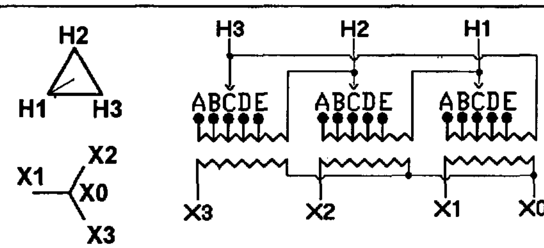
% EFFICIENCY (AT 35% FULL LOAD)		% REGULATION (FULL LOAD)			
Minimum per C802	97.50	1.00	0.95	0.90	0.85
Estimated	97.84	2.68%	3.17%	3.29%	3.34%

TAPS

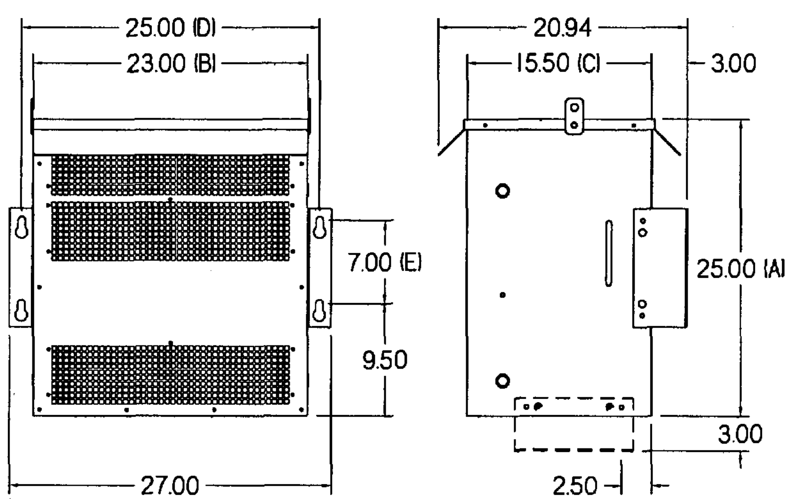
Pos	A	B	C	D	E	F	G
%	+5	+2.5	0	-2.5	-5		
Volts	630	615	600	585	570		

Primary connectors by phase 1 #2 AWG - #14 AWG
Secondary connectors by phase 1 #00 AWG - #6 AWG
Primary Winding in Copper
Secondary Winding in Copper

CONNECTION DIAGRAM



PHYSICAL DIMENSIONS



ENCLOSURE

	INCHES	MM
A	25	635
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MOUNTING : WALL AND FLOOR

		COMMENTS
Customer / PO	ECOLE POLYTECHNIQUE	
Contact	DAWEI ZHU	
Project		
Revised by	Frédérick Dubeau	
Revision Date	Thursday, 9 apr. 2009 13:05	